LARGE, HIGH INTENSITY FIRE EVENTS IN SOUTHERN CALIFORNIA SHRUBLANDS: DEBUNKING THE FINE-GRAIN AGE PATCH MODEL

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Abstract. We evaluate the fine-grain age patch model of fire regimes in southern California shrublands. Proponents contend that the historical condition was characterized by frequent small to moderate size, slow-moving smoldering fires but that this has been disrupted by fire suppression activities, resulting in unnatural fuel accumulation and anomalously large and catastrophic wildfires. A review of more than 100 19th century newspaper reports reveals that large, high intensity wildfires predate modern fire suppression policy and first hand accounts support the conclusion that the 1889 Santiago Canyon Fire was the largest fire in California history.

Proponents of the fine-grain age patch model contend that even the very earliest 20th century fires were the result of fire suppression disrupting natural fuel structure. We tested that hypothesis and found that within the fire perimeters of two major fire events in 1919 and 1932, prior fire suppression activities were insufficient to have altered the natural fuel structure. Over the last 130 years there has been no significant change in the incidence of large fires greater than 10,000 ha, consistent with the conclusion that fire suppression activities are not the cause of these fire events. Eight megafires (≥50,000 ha) are recorded for the region and half have occurred in the last 5 years. These burned through a mosaic of age classes which raises doubts that accumulation of old age classes explains these events. Extreme drought is a plausible explanation for this apparent rash of such events and it is hypothesized that drought leads to increased dead fine fuels that promote the incidence of firebrands and spot fires.

A major short-coming of the fine-grain age patch model is that it requires age-dependent flammability of shrubland fuels, but seral stage chaparral is dominated by

short-lived species that create a dense surface layer of fine fuels. Results from the Behave Plus fire model with a custom fuel module for young chaparral shows there is sufficient dead fuel to spread fire even under moderate winds. Empirical studies of fuel ages burned in recent fires illustrates that young fuels often comprise a major portion of burned vegetation and there is no difference between evergreen chaparral and semi-deciduous sage scrub.

It has also been argued that the present day fire size distribution in northern Baja California is a model of the historical patterns that were present on southern California landscapes. Applying this model with historical fire frequencies shows the Baja model is inadequate to maintain these fire-prone ecosystems and further demonstrates that fire managers in southern California are not likely to learn much from studying modern Baja California fire regimes. Theoretical cellular automata models of fire spread show that even in systems with age dependent flammability, landscapes evolve towards a complex age mosaic with a plausible age structure only when there is a severe stopping rule that constrains fire size, and ignitions are saturating.

Key words: fire history, chaparral, sage scrub, megafires, fire regimes, high intensity fires, fine-grain age patch mosaic, Baja California

INTRODUCTION

Shrubland dominated landscapes in California have fuel characteristics conducive to high intensity wildfires that commonly reach sizes of 10,000 ha or more (Keeley et al. 1999). Some researchers have postulated that such fire events are anomalous and were unknown prior to putative perturbations of the natural fuel structure by 20th century fire suppression (Bonnicksen 1981, Minnich 1983, 1995, 2001). These authors have argued that historical fire regimes were profoundly different than contemporary fire regimes. In their model, frequent lightning or Indian burning created a fine-grain age patch mosaic of small low intensity smoldering fires, and the resulting patchwork of young and old fuels prevented large fires due to the inability of young seral stands to carry fire. Proponents of this model predict that if the purported 19th century fire regime were restored to contemporary landscapes, then large high intensity crown fires could be prevented. While many have discounted this model (Keeley et al. 1989, 1999, Zedler 1995, Moritz 1997, 2003, Moritz et al. 2004, Conard and Weise 1998, Zedler and Seiger 2000, Keeley and Fotheringham 2003), it is being advocated in newspaper op-ed pieces (Minnich 2003, Chastain 2007), in national newspaper stories (LaFee 2004, Vick and Geis 2007) and web sites of timber advocacy groups (e.g., California Forest Foundation 2007), as well as in a recent *Ecological Applications* paper (Goforth and Minnich 2007). We believe the time is right for a more thorough analysis of this fine-grain age patch mosaic model as it has the potential for affecting public opinion, and ultimately resource allocation for fire management activities, as well as stalling needed land zoning reforms (Phelps 2007, Gang 2007).

Large high intensity fires

Large infrequent disturbances have always been major drivers of ecosystem structure and function (Turner and Dale 1998), but increasingly in a world filled with people, they pose significant challenges. This is certainly the case for wildfire, which has repeatedly overwhelmed the capacity of resource managers to regulate it, especially in the fire-prone Mediterranean climate region of the Pacific Coast. One of the most basic questions is what can be done, through modified management practices and land development policies, to make fires less damaging to humans and their property.

In the Western US, large wildfires in recent decades have been ascribed to past management practices that have altered fuels in many forested ecosystems (Allen et al. 2002). It is widely believed that very large high intensity fires in these ecosystems are anomalous events that were unknown historically. This model is most applicable to pine forests such as the ponderosa pine of the southwestern US as well as longleaf pine in the southeastern US. These landscapes historically experienced a very high frequency of lightning ignited fires, which in the absence of human interference, maintained open stands with limited surface fuels, and this promoted a regime of low intensity surface fires (Allen et al. 2002, Glitzenstein et al. 1995).

Large high intensity crown-fires are considered to be a natural feature in many ecosystems (Turner and Romme 1994, Johnson et al. 2001, Meyn et al. 2007, Keane et al. 2008), including California shrublands (Keeley and Fotheringham 2003). However, some argue that in the absence of human interference, fires in California chaparral shrublands were small and of low to moderate intensity (Bonnicksen 1981, Minnich 1983, 1995). They claim that frequent natural lightning ignited fires burned small patches (10^2 - 10^3

ha) at a sufficient scale to produce landscape mosaics of fuels, and once a patch burned it would act as a barrier to fire spread for several decades due to insufficient fuels. They contend that the appropriate fire management for this landscape is one that couples a let-burn policy for summer wildfires with extensive landscape scale fuel modification through rotational prescribed burning that produces a fuel mosaic putatively capable of preventing large wildfires (Minnich and Dezzani 1991, Minnich and Chou 1997, Minnich and Franco-Vizcaino 1999, Minnich 2001).

Hypothesis and predictions

Here we test the hypothesis that prior to aggressive fire suppression, fire regimes in the shrubland dominated landscape of southern California burned frequently in a fine-grain patchwork of low to moderate intensity fires, against the alternative hypothesis that contemporary shrubland fires are within the historical range of variability for this landscape.

This fine-grain model has profound implications for fire management because it contends that large catastrophic wildfires on these landscapes are the fault of fire fighters who have in effect perturbed the ‘natural’ fire regime and the appropriate remedy is to abandon total fire suppression. The alternative hypothesis argues that large catastrophic fires are the result of natural forces and vulnerability of human communities is tied more to lack of planning and infrastructure protection.

Predictions deduced from the null hypothesis, and tested here, are:

1) There is no credible evidence that 19^{th} century fires were large (10^3 – 10^5 ha) or high intensity (flame lengths >> 5 m).

2) Early 20th century fires are linked to immediate disruptions in natural fire regimes due to fire suppression of natural lightning ignited fires, and large fires have increased throughout the 20th century.

3) Fire spread in California shrublands is fuel (age) dependent such that fires will not spread in early seral stages because of their low dead-to-live fuel ratio, imposing a threshold age of about two to three decades before these stands become flammable.

4) The fine-grain patchwork of fire sizes in Baja California will produce a stable equilibrium in fire regime within the expected historical fire return interval of 50 – 100 years when ignited solely by natural lightning.

5) Theoretical models constrained by patch age should develop fine-grain structure spontaneously, which once present will persist on the landscape due to resilience to changes in ignition and fire behavior.

METHODS

Historical accounts of 19th century fires in southern California were obtained from newspapers on microfilm at the California State Library (Sacramento, CA), unpublished reports in the U.S. National Archives (San Bruno, CA, Laguna Niguel, CA, and Washington Archives II, College Park, MD) and USFS Angeles National Forest (Supervisor's Office, Arcadia, CA), and library materials. Copies of the 1878 Tujunga Cañon Fire perimeter map were copied from maps on file at the USFS Angeles Forest Supervisor's Office, Arcadia, CA and from the U.S. National Archives, Washington Archives II, College Park, MD.

Numerical fire history data were obtained from multiple sources. The FRAP Statewide Fire History electronic database (California Department of Forestry and Fire Protection, Fire and Resource Assessment Program, FRAP) is generally complete for fires greater than 100 ha but most fires less than 25 ha are not included. Individual fire reports for selected years were obtained from one of the national archives offices listed above or directly from a regional USFS office. Long term trends in fire size were done with least squares regression analysis using Systat 11.0 (Richmond, CA, USA).

Palmer Drought Severity Indices (PDSI) were obtained from two sites; 20th century data by month were from (http://www.ncdc.noaa.gov/oa/climate/research/drought /palmer-maps/). Summer PDSI for the 19th century was from (ftp://ftp.ncdc.noaa. gov/pub/data/paleo/drought/pdsi2004/data-by-gridpt/048.txt).

Modeling of expected fire behavior using either field measures of fuels or standard fuel models was done with Behave Plus. This is a PC-based Windows software application used to predict wildland fire behavior (http://www.firemodels.org/content /view/12/26/). Rothermel equations that are used in the Behave Model have short comings when applied to chaparral (Zhou et al. 2005), but we believe it is appropriate to our application in young seral chaparral. Here dead fuels dominated and the bulk were within 75 cm of the soil surface.

Theoretical expectations of the fine-grain age patch model were explored with a cellular automata model, which creates a square map divided into cells that have two properties, location in the x-y grid and age, the number of time steps (yrs) since that cell was "burned". These kinds of models have been proposed by a number of others, usually with the intent of building a model that would replicate fire behavior in real

landscapes(Clarke et al. 1994, Encinas et al. 2007, Yassemi et al. 2008) The minimum age at which burning is possible ("*minage*") is either a constant throughout a given run or allowed to vary from one year to the next. In both cases it is assumed to be constant over the landscape. The model moves by 1-yr time steps, incrementing the age of all cells each year prior to the "burn season". Within a given year, the burning process is initiated by one or more random ignitions. If the age of the element receiving the ignition is ≥ *minage*, that cell burns in its entirety and its age is set to zero, if it is < *minage* the cell does not burn. The fire spreads contagiously and probabilisitically The propagation of the fire to the eight cells that touch on a burning cell (the "Moore neighborhood", Gaylord and Nishidate 1996) is limited stochastically by a "probability of propagation" that can vary from zero (the fire cannot spread from the cell ignited) to one (the fire will spread to all of the adjacent cells ≥ *minage* unless they are already burning). The probability of propagation is constant for each simulation run. Wind and slope effects and spotting – the spread of fire by the dispersion of burning brands beyond the flame front -- are not included in the model.

In the first series of simulations all cells were of age 1 at the beginning to observe the development of the age mosaic from a uniform condition. In the second set of simulations, the starting landscape began with an age mosaic in which ages between 0 and *minage* years were assigned randomly and independently to each cell. The model was run to determine the length of time until coalescence was substantially achieved as indicated by 90% or more of the cells burning in a single year. Since the first simulations showed that coalescence would not occur for low values of probability of propagation only values of 0.4 and above were used. The simulation was run multiple times at each

combination of propagation probability and number of strikes per cell to average out random variability. Runs were made with up to 40,000 cells, but as the outcomes for smaller areas were substantially the same, results are presented for a 900 and 2500 cell landscape. The model was programmed in MATLAB 7.5 and run on a Macintosh G5 computer.

RESULTS AND DISCUSSION

Large historical fires in the 19th century

Here we investigate the question, are contemporary fires in southern California greatly outside the historical range of variability in terms of size and intensity because of 20th century fire suppression? We test the following prediction deduced from the fine-grain patch model: There is no credible evidence that 19th century fires were large (10^3 – 10^5 ha) or high intensity (flame lengths >> 5 m).

On these landscapes the fine-grain age patch model predicts that fire suppression is the primary factor disrupting natural fire regimes. Pre-suppression era logging, which is known to have increased fuels in some western forests is not a factor on these shrubland landscapes. Pre-suppression era grazing, which reduced the incidence of grass-driven fires and caused an in-growth of fuels in some southwestern pine forests (Savage and Swetnam 1990), does not apply to these shrubland landscapes as the primary impact of grazing has been to type convert shrublands to grasslands with lower fire hazard (Keeley and Fotheringham 2003).

In the 19th century, before development of roads in most mountainous areas of southern California, and lack of an organized fire fighting force, fire suppression was very limited. Rural residents did fight fires, but it was largely defensive and focused on

stopping fires from destroying structures and crops on outlying ranches and farms (Kinney 1900) and "*no effort was made to stop [fires] after they reached the mountains*" (Mendenhall 1930). In short, fire suppression did not affect wildland fire regimes in any significant way in this region. This overview of 19th century fires depends heavily on historical accounts of large fires that are captured in the 108 newspaper reports transcribed in Appendix A.

1878 Tujunga Cañon Fire

The earliest fire recorded in the CalFire FRAP historical fire database is a 24,100 ha 1878 fire in the vicinity of Tujunga Canyon in the western end of the San Gabriel Mountains of Los Angeles County. Many years later Mendenhall (1930) described this fire and noted it was in the first half of September. The Los Angeles Daily Herald (Appendix A-6) reported for a dateline 'SAN FERNANDO, Sept. 11 [1878]' that "*A fire originated in the brush near the little Tujunga Cañon on the 9th instant, at about ten o'clock A. M., and was soon beyond control*." The article notes that within the first four hours the fire consumed over 7,000 ha and was still burning. Based on this initial rate of spread, and the fact that it was reported to be burning in the backcountry the following day (Appendix A-10) makes it likely that this was the 24,100 ha fire reported in the FRAP database. Based on the fire map, and accounts of the fire from residents (Mendenhall 1930), it is also possible that this fire joined another fire that ignited the same day to the east of Tujunga Canyon on the San Pascual Ranch, near the present day town of Montrose (Appendix A-8). Fire complexes are not uncommon today, and thus this might appropriately be called the 1878 Tujunga Cañon Fire Complex.

This fire spread at such a rate that it could hardly have been of low or even moderate intensity. It certainly was not “a slow smoldering fire”, of the kind postulated to be characteristic of the fine-grain age patch mosaic model. More likely it resembled another fire at the same time in that vicinity: “*As soon as the brush was ignited the blaze traveled like wildfire, consuming everything in its way. In a short time it whiened [sic] out and swept along in a swathe of flame two miles broad…nobody can face the heat, it is so intense, and this morning a party who tried to control the cause of the fire found it impossible to live within sixty yards of it*” (Appendix A-7). Other fires that same year also suggest high intensity, such as “*The scene of the conflagration seemed not over a mile distant, while it was, in fact, nearer twenty miles. As a spectacle it was a superb success. The mountains more nearly resembled San Francisco, lit up by gas, as seen by the passenger from Oakland after nightfall, than anything we can recall just now*.” (Appendix A-8). Like these 1878 shrubland fires, many others during the 19th century were clearly high intensity fires (Appendix A).

This 24,100 ha 1878 fire is not compatible with the picture of a historical fine-grain age patch model of small, low intensity fires on these landscapes. Therefore, it is not surprising that proponents of that model have questioned this event (Goforth and Minnich 2007). They presented “independent physical evidence” that purportedly showed the size of this fire was greatly exaggerated. Their evidence consisted of fire scar dendrology studies by Kerr (1996) that were putatively within the fire perimeter, yet did not record the 1878 fire. They failed to recognize, however, that although in close proximity, the fire perimeter and fire scar sample areas did not overlap (Fig. 1). Other evidence they presented against the existence of this fire is the suggestion that the fire perimeter map

was fabricated and thus raised doubts as to whether it had occurred at all. In support of this they demonstrated that the 1878 fire perimeter map lacked detailed convolutions characteristic of modern fire perimeters. However, in 1878 reconnaissance was done on foot and horseback, using Land Survey maps that were less detailed than later USGS topographic maps, and thus there would have been limited capacity to produce a detailed fire perimeter map, and we doubt that this lack of precision can be taken as evidence that the fire event never occurred.

1889 Santiago Canyon Fire

A contender for the largest wildfire in California history occurred in late September 1889; long before fire suppression policy in the region. It ignited in Santiago Canyon, in the northern part of the Santa Ana Mountains in Orange County, and is here referred to as the 1889 Santiago Canyon Fire. Conditions leading up to this September 1889 fire event include a somewhat more severe than usual annual drought, with less than 1 cm of precipitation being recorded in San Diego for the previous 5½ months (USDA Weather Bureau 1934). Ten days before the big fire event there was “a *Norther*” (Appendix A-65) or foehn-type Santa Ana wind (Box 1), further drying shrubland fuels. Following this, temperatures remained high and contributed to several significant fires in San Diego and San Bernardino counties (Appendix A-19,20,21).

Following this period of severe fire weather conditions, the Santiago Canyon Fire began the morning of 24 September 1889, coincident with a new Santa Ana or ‘Norther’ wind event (Box 1), which blew with considerable intensity throughout the region, including San Bernardino, Riverside, San Diego and Orange counties. This particular Santa Ana wind event lasted three full days with temperatures increasing to a peak of

32^{o}C on 26 Sept and was described as being of unusual severity; "*blowing a hurricane*" and the blinding dust and heat next to intolerable (Appendix A-24-29,31,32,34,37,40-42,65).

Apparently it was accidentally ignited on Noland's ranch (Appendix A-40, but c.f. A-47) in the northwestern foothills of the Santa Ana Mountains east of El Modena in Santiago Canyon (Fig. 2) "*and as the wind was blowing a perfect gale from off the desert the mountains were soon red with the angry flames*" (Appendix A-22). Reports show the fire burned very rapidly ("in less than five minutes from the time the fire broke loose, the whole side of the mountain was ablaze" (Appendix A-40), and within the first 6 hours extended 25 km northeast to southwest (Appendix A-26). Although the prevailing northeasterly offshore flow of air dominated the fire behavior, there were erratic winds in the foothills and mountains that also carried the fire north and eastward (Appendix A-22; see also Box 1 and Appendix B for further insights into erratic wind behavior during Santa Ana wind events). By the first evening of the fire it was reported that "*about 25 miles* [40 km] *of the mountains east of Santa Ana are on fire, and doing great damage east and south of El Toro*" (Appendix A-28). It would appear that the winds were spreading the fire with embers far beyond the fire front based on the description that the first "*night large fires were seen in many places on the hills, and the glow arising from the canyons showed that great fires were raging in them. The flames in many places spread with alarming rapidity* " (Appendix A-26).

"*The views from the housetops was a grand one. Never before have the people here witnessed such a natural pyrotechnic display. Looking eastward the entire heavens is one bright-red glare. Citizens in the entire valley are thoroughly aroused, and all are doing*

all they can to protect their property" (Appendix A-22). The immensity of this fire is illustrated by the report that not only citizens facing the fire on the western side of the range were impressed by the nighttime pyrotechnics, but the fire was also visible 50 km away on the eastern side of the range (with peaks 1200 – 1600 m): "*Forest fires in the mountains east of Santa Ana raged all day and last night the light reflected upon the sky from the fire in that direction was plainly seen in this* [Riverside] *city*" (Appendix A-25).

In addition to burning in the mountains (Appendix A-22,24,34,39) the fire burned westward into the coastal plain as passengers on the San Diego train [along a coastal route through San Juan Capistrano] reported "*the fire was raging on both sides of the track, and they thought they would be smothered before they got through the burning district"* (Appendix A-27). The following day (the 25th) it was reported that "*this morning a stiff breeze is blowing and the smoke is increasing, showing that the fires are spreading*" (Appendix A-26). At this time winds were still going strong (Appendix A-40) and were driving the fire in a southwestward direction as it was reported that "*The devastating fire still continues in portions of the canyons…At San Juan Capistrano last night great danger was experienced in keeping fire from the heart of the city*" (Appendix A-55, see also A-48). The fire was still burning on the third day as reported from Santa Ana "*The fires in the mountains east of the city are not yet extinguished as was evidenced by the scene this morning at 3 o'clock. The whole eastern horizon was brightly illuminated and presented a majestic and sublime sight*," (Appendix A-39). This was verified by the report, "*fire which has been burning for the past two days still continues in the cañons*" (Appendix A-51). Although the fire burned the coastal plain as far south as San Juan Capistrano, it is not clear from newspaper accounts whether or not this fire

front continued burning southward. However, the fire was very active in the mountains of eastern Orange and western Riverside counties. For two days it burned along an estimated 50 km of the Santa Ana and Santa Rosa Mountains, now the Santa Rosa Plateau (Appendix A-62). Around the 26th the fire burned into San Diego County and at that point was described as having swept "*an immense territory*" (Appendix A-60). When it reached "*Coral del Luce*," a stable owned by an Englishman named Luce (Rivers 1999) at the site of the present day community of De Luz (Fig. 2), the southward momentum switched and it was driven hard by a strong "*east wind* [(consistent with documented wind patterns, see lower portion of Appendix B-2), which] *then brought on fire in the direction of the* [Santa Margarita] *ranch*" (Appendix A-60). Before reaching the ranch house near the coast the offshore winds abated and the fire was picked up by onshore breezes that pushed the fire eastward and days later "*the fire* [was] *still raging in the mountains*" (Appendix A-60). During this time it burned as far east as Temecula in Riverside County and may have been responsible for the burning as far south as Encinitas in San Diego County (Appendix A-62).

Based on the area circumscribed by the reports of 1889 (Fig. 2), we believe that a conservative estimate for this fire would be ~125,000 ha, and if the reported burning as far south as Encinitas were part of this same fire, it could have been more like ~200,000 ha. The aftermath of this and other fires in the region that same week is portrayed in a newspaper report the following week: "*The fires in the valleys and foothills lately have almost hidden the lofty peak of San Bernardino from sight. He appears dimly, if at all, and as if floating in cloudland*," (Appendix A-63). "*It is a year of disasters, wide-spread destruction of life and property – and, well, a year of horrors*" (Appendix A-53).

Of course the exact dimensions of the 1889 Santiago Canyon Fire are not ever likely to be known for sure, however, the magnitude of our estimate is vetted by a first hand account that places it on the same scale as the largest 20^{th} century fires in California. USFS Assistant Regional Forester for California, L.A. Barrett (1935) reported in a compilation of newspaper accounts of California fires, "*I was living in Orange County at the time and well remember the great fire reported herein from September 24 to 26* [1889]. *Nothing like it occurred in California since the National Forests have been administered. In fact in my 33 years in the Service I have never seen a forest or brush fire to equal it. This one covered an enormous scope of country and burned very rapidly*." Mr. Barrett's USFS career in California included the 1932 Matilija Fire that was over 89,000 ha, which provides a lower baseline for the size of the 1889 Santiago Canyon Fire.

The 1889 Santiago Canyon Fire stands as a clear example of a massive high intensity crown fire in the absence of organized and aggressive fire suppression. Its size was of the same magnitude as the largest fires recorded in southern California since annual record keeping began in the early 1900s (Table 1). Even if this fire was only half as large as our most conservative estimate (125,000 ha), it would still rank as one of the largest fires in California's history. This fire event is remarkably similar to modern fire events such as occurred in 2003 and 2007 in that significant fires were occurring in several counties at the same time. In addition to the Santiago Canyon Fire, there were big fires in San Bernardino (Appendix A-21,25,43) and southern San Diego counties (Appendix A-29,30,33,36,44,50,57,59), all driven by the same Santa Ana wind event. What is strikingly different from 21^{st} century fire events is that despite the magnitude of the 1889

fires, few structures and lives were lost. Thus, on this landscape the primary change that has made fires destructive is not a change in the size and intensity of wildfires, but in the size and distribution of the human population (Keeley et al. 1999).

An alternative interpretation of the 1889 Santiago Canyon Fire

Goforth and Minnich (2007), as advocates of the fine-grain age patch hypothesis, do not believe that the historical accounts of the 1889 Santiago fire are accurate. In search of "objective" evidence of fire size, they investigated insurance claims made after the fire and mentions of damage to specific properties in the newspapers. They do not consider that there could be a substantial spatial bias in these accounts if the fire burned beyond the more densely settled lower foothills and coastal plain and into the mountain slopes where inhabitants were few, and insurance probably not the norm. That the fire did extend into these areas is attested by numerous accounts in the newspapers that report the fires burning in the "mountains" (Appendix A-22,24,25,28,34,39, 52,55,60). Today there are 3 million people living in Orange County, primarily in the coastal plain, and the rugged chaparral covered Santa Ana mountain range is largely unoccupied; thus, it seems certain that in 1889, with a population of only 13,000 in the county, that other than a few miners and grizzly bear hunters (Sleeper 1976), these mountains were unsettled. One would not expect insurance claims from the vast majority of area burned by the 1889 Santiago Canyon Fire.

Goforth and Minnich (2007) estimate by their methods that the full extent of the fire was only about 15 km (see their Figure 2a). This is grossly inconsistent with newspaper accounts that reported that the fire had spread 25 km during the first 6 hours and 40 km by that evening. After two more days of intense Santa Ana winds one might expect it

would have spread considerably further, and numerous newspaper accounts discussed above corroborate that conclusion.

One reason Goforth and Minnich (2007) failed to appreciate the extent of the Santiago Canyon Fire is their assumption that the fire reported on the Santa Margarita Ranch in northern San Diego County (Appendix A-60) was a smaller (Appendix D), separate and isolated event. This, in part, is due to an error in interpreting historical names. The Daily San Diegan on 29 September 1889, in article titled "*An Immense Territory Swept by the Flames,*" stated that "*…The fire originated at the Coral del Luce and extended to the Santa Rosa Mountains, and the east wind then brought on fire in the direction of the ranch, and it is estimated that fully 65,000 acres were burned before the fire was extinguished….*" Goforth and Minnich (2007) assert that the newspaper was in error and that the site they were referring to was "Corral de la Luz," a train station in the coastal plain near the Santa Margarita Ranch house. But during this period there was a site known as 'Corral del Luce,' which was a stable run by an Englishman named Luce located between the eastern end of the Santa Margarita Ranch and Rancho Santa Rosa (Elliott 1883, Rivers 1999) in the mountains near the present day town of De Luz in northern San Diego County (Fig. 2 and Appendix D). According to the newspaper account, the fire that threatened the ranch was an extension of burning in the "Santa Rosa Mountains" (present day Santa Rosa Plateau), and Luce's corral was only about 5 km southwest of these mountains. Other newspaper accounts report that burning in these mountains extended for 50 km (Appendix A-62), which would have overlapped considerably with the Santiago Canyon Fire (Appendix A-28). In light of the three days

of intense Santa Ana winds blowing in a southwesterly direction there is good reason to interpret this as part of the Santiago Canyon Fire (Fig. 2).

Goforth and Minnich (2007) claim that newspaper reports of the 1889 fire are exaggerations, if not outright fabrications, and represent a classical case of "yellow journalism" designed solely to create readership. Yellow journalism is a pejorative term that was coined about a decade after the 1889 fire and connoted unethical or unprofessional journalism, particularly the use of highly sensational headlines. Goforth and Minnich (2007) quote headlines such as "*Fearful Flames*," "*Small Towns in Peril*" or "*Great Fires Raging Around Santa Ana*" as examples. Such headlines, however, are quite comparable to contemporary headlines; e.g., "*Wildfires Rage*" (San Diego Union-Tribune, 22 Oct 2007), "*300,000 Flee Fires, Blazes March Toward Coast*" (San Diego Union-Tribune, 23 Oct 2007), or "*Amid Fear and Uncertainty, a 'Staggering' Evacuation*" (USA Today, 24 Oct 2007), and in fact the 1889 articles (Appendix A) read very much like contemporary articles describing catastrophic fire events. One major difference is that contemporary headlines inevitably occur on the front page because they are a major concern to population centers that have expanded into the wildlands. Nearly all of the 19th century reports occurred on subsequent pages, perhaps because mountain fires were of less immediate concern.

In what seems to be a desperate attempt to diminish the magnitude of the 1889 Santiago Canyon Fire, Goforth and Minnich (2007) fall back on "*an old proverb* [that] *states that smoke travels farther than flames*." They use this to dispute a first hand account of the fire appearing to extend from "the mouth of the Santiago Canyon southward toward San Juan Capistrano" (Appendix A-48). Their contention is that

because the sky was smoky, the observer on the hotel roof in Anaheim would not have been able to see flames as far away as San Juan Capistrano, and therefore was reporting on smoke that had drifted that far south. However, they ignore the fact that during Santa Ana wind conditions smoke from wildfires is normally blown offshore and does not "drift" southward (see image in Box 1). In addition, reliance on proverbs ignores a more trusted approach to vetting newspaper stories, namely corroboration from another source; in this case there is separate newspaper report to the effect that "*At San Juan Capistrano last night great danger was experienced in keeping a fire from the heart of the city*" (Appendix A-55).

Finally, Goforth and Minnich (2007) dispense with the report of Regional Forester L.A. Barrett on the fire size by noting that it lacks credibility since he was only 15 years old at the time of the fire. Even if Barrett's statement were the only data on fire size, we don't see that his age is an important determinant of its validity. Regardless, it matches well with independent contemporary accounts from newspapers, and since it was given by a professional forester, it would seem unlikely that it was a baseless exaggeration. See Appendix D for further discussion of their criticisms.

Summary of 19th century shrubland fires

Looking more broadly at burning patterns in the 19th century, it is apparent that relatively large high intensity chaparral fires were regular occurrences. In addition to the 1878 Tujunga Cañon and the 1889 Santiago Canyon fires there were many others (Appendix A), often, but not always, associated with Santa Ana winds. For example, significant fire events occurred in 1879 and 1890 in San Diego County and in 1896 and 1899 in Los Angeles County. These fires were generally reported to be very fast moving

and of considerable fire intensity and based on the huge plume evident in 19th century photographs (e.g., Fig. 3), it would appear they were substantial enough to create their own weather. Marine charcoal deposition records suggest such massive high intensity wildfires have long been a part of this landscape (Byrne et al. 1977, Mensing et al. 1999).

In summary, the historical evidence on 19th century fires in southern California does not support the notion that fire size was constrained to a greater degree than at present. Small fires would have occurred then, as now, but there is no evidence that their spatial distribution produced a landscape immune to large high intensity fires. The primary evidence for a strictly fine-grain fire regime in southern California are the patterns of burning in Baja California, where it has been repeatedly assumed that the only difference between Baja and southern California is a difference in fire suppression policy (Minnich 1983, 1995, Minnich and Chou 1997). This conclusion has been challenged as there are numerous physical, biological, and sociological differences between these regions that have not been given sufficient consideration (Strauss 1989, Keeley 1995, 2006, Keeley and Fotheringham 2001a, 2001b, Zedler and Oberbauer 1998, Moritz 1997, 2003, Halsey 2004). Most relevant is the much greater rural population immediately south of the border with huge impacts on fire ignitions and vegetation fragmentation (Dodge 1975). Further south the fire regime changes due to the apparent lack of Santa Ana winds south of Ensenada (see one example at Santa Tomas in the remote image in Box 1).

Prior to the modern era of intensive rural land use in Baja California, there is evidence that Baja California burned in large high intensity wildfires similar to those in southern California. This conclusion is supported by the log book of English explorer George Vancouver (Vancouver 1798) who reported in 1793 that, during a Santa Ana

wind event, off the coast of northern Baja California in the vicinity of Bahia Todos Santos, near present-day Ensenada “[10 Dec 1793] … *During the forenoon immense columns of smoke were seen to arise from the shore in different parts, but principally from the south-east or upper part of the bay, which towards noon obscured its shores in that direction. These clouds of smoke, containing ashes and dust, soon enveloped the whole coast to that degree, that the only visible part was the fourth point of the above-mentioned bay, bearing by compass N. 42 E., about four us: the observed latitude at this time was 31o 40’, longitude 243o 31 ½’. The easterly wind still prevailing, brought with it from the shore vast volumes of this noxious matter….*” [11 Dec 1793] *Two opinions had arisen as to the cause of the very disagreeable clouds of smoke, ashes, and dust, in which we had been involved the preceding day. Volcanic eruptions was naturally the first conjecture; but after some time, the opinion changed to the fire being superficial in different parts of the country; and which by the prevalence and strength of the north-east and easterly wind, spread to a very great extent. The latter opinion this morning evidently appeared to be correct. Large columns of smoke were still seen rising from the vallies behind the hills, and extending the northward along the coast; this seemed the line of direction which the fire took, excluding the country from our view to the North of Todos Santos. To the south of us the shores exhibited manifest proofs of its fatal effects, for burnt tufts of grass, weeds, and shrubs, being the only vegetable productions, were distinguished over the whole face of the country, as far as with the assistance of our glasses we were enable to discern; and in many places, at a great distance, the rising columns of smoke showed that the fire was not yet extinguished.*”

Clearly, this was a very large fire by an objective observer who had little incentive to sensationalize his account. Such fire events may not have been unusual on the Baja landscape even into the 20th century because the 16-18 yr span in aerial photographs used by Minnich (1995) to document the apparent lack of such fires in Baja could have easily missed large fire events (Keeley and Fotheringham 2001a, b) and recent satellite images demonstrate such fires are possible south of the border (Box 1).

The 19th century vegetation patterns

The fine-grain age patch model predicts that the landscape prior to 20th century fire suppression comprised a complex mosaic of young and old patches of shrublands sufficient to provide barriers to fire spread. Definitive tests of this prediction are difficult because despite a plethora of early California histories, the vast majority were concerned with the personalities that colonized this landscape and very few with the landscapes themselves. The primary evidence comes from 19th century forest reserve surveys conducted by USGS biologist J.B. Leiberg.

Based on Leiberg's reports (1899a,b,c, 1900a,b,c) it has been estimated that 90% of the 214,000 ha of shrublands on the San Jacinto Forest Reserve were older than 30 years of age at the end of the 19th century and other reserves were in a similar state (Keeley and Fotheringham 2001a). Since there is general agreement that 30 year old shrublands are highly flammable, it is hard to conceive of an age patch mosaic that would have prevented large wildfires.

To support their contention that the 19th century landscape had an age patch distribution sufficient to stop large wildfires, Goforth and Minnich (2007) cite Leiberg's (1899a,b,c, 1900a,b,c) forest reserve reports, pulling out quotes that seem to support the

notion of a fine-grain age patch mosaic due to small fires. For example, the Leiberg quote that "[Chaparral] … *is a growth which varies from extremely dense to thin or open, but rarely forms very large, uninterrupted patches*. *The dense portions are commonly separated by narrow lanes* ['recent burns' inserted here by Goforth and Minnich (2007)], *which are either wholly free from brush, or bear a scattered growth so thin as to offer no serious obstacles to travel*." Goforth and Minnich's interpretation inserted in this sentence seems incorrect to us since fires do not burn in "*narrow lanes*" and the level of detail presented in Leiberg's documents suggests to us that he would have indicated these "*narrow lanes*" were past fires if in fact that were the case. More likely Leiberg was describing interruptions in the chaparral due to surface or subsurface rock outcrops, ridgelines or wildlife trails from deer or grizzly bears that made their homes in chaparral. More to the point though, Leiberg himself contradicts Goforth and Minnich's interpretation that these narrow lanes in the chaparral fit the fine-grain age patch mosaic model in his own conclusion that "*The natural lanes existing throughout the chaparral are too narrow to serve as efficient fire breaks*" (Leiberg 1900c, p 477). Other quotations from the literature (e.g., Mendenhall 1930, Kinney 1887) used by Minnich and co-authors follow a similar selective use of information and often do not provide a complete picture.

We find no support for the idea that the pre-fire-suppression landscape was a mosaic of young and old chaparral capable of preventing the spread of large fires.

20^{th} Century Fires

Proponents of the fine-grain age patch mosaic model contend that fire suppression impacts were almost immediate and this accounts for well documented large fires throughout the 20^{th} century (Minnich 1989, Goforth and Minnich 2007).

Organized fire suppression in southern California began in the early 1900s. In the first few decades fire fighting was largely defensive and focused on stopping fires from moving into rural areas. Minimal effort was made to suppress natural ignitions in remote regions. Where resorts had been constructed such as in the canyons on the southeast side of the San Gabriel Mountains bordering the growing Los Angeles Basin, organized fire suppression began in the late 19th century, although it was initially rather effective (e.g. Appendix A-95-108). Throughout the southern California region a policy for suppression of all fires on USFS lands evolved slowly in the early part of the 20th century and was limited due to the inaccessibility of rugged and roadless areas, coupled with limited fire fighting resources and transportation (Mendenhall 1930, Brown 1945, Show 1945). Sterling (1904) stated in reference to the San Gabriel Mountains "*the country itself, which is so rough as to be almost inaccessible in parts, and so wild and isolated that the maintenance of a thorough patrol is difficult,*" and this applied to other ranges as well. On state responsibility lands in southern California fire suppression was limited and disorganized until the 1920s (Clar 1959). At both the state and federal level, fire suppression became much more aggressive following WWII with improved vehicles and road access and the increasing use of airplanes and helicopters (Pyne 1982, Godfrey 2005, Cermak 2005)

Since USFS record keeping began around 1910, there have been large fire events once or twice a decade somewhere in the region (Fig. 4). We interpret these as a natural continuation of the historical pattern of fire on these landscapes that likely has been present throughout the Holocene. However, proponents of the fine-grain age patch model have argued that even the very earliest 20th century fires were the result of fire

suppression activities disrupting natural fuel mosaics. For example, Goforth and Minnich (2007; also Minnich 1987) claim that one of the first big 20th century fires, the 1919 Ravenna Fire (Fig. 5), which burned 30,350 ha of rugged chaparral landscape on the Tujunga District of the Angeles Forest (Mendenhall 1930), was an unnatural event resulting from fire suppression disrupting natural fire regimes. Since Goforth and Minnich (2007) provided no evidence to support their claim that fire suppression was immediately effective in disrupting natural fire regimes, it is at best a hypothesis. If true then one would expect that prior to 1919 a large enough number of lightning-ignited fires would have been suppressed within the perimeter of this fire to eliminate the "natural" fuel mosaic. One could postulate various models for the number of suppressed fires required to disrupt the putative fuel mosaic, but in all cases it surely would be a number far greater than the single lightning-ignited fire the records show was suppressed during the period of record keeping from 1911 – 1919 (Fig. 5). Clearly disruption of the natural lightning fire regime cannot explain the large high intensity Ravenna Fire of 1919. Nor can elimination of Native American burning within the fire perimeter area as there were no permanent Indian settlements in this rugged landscape (McCawley 1996). Between 1911 and 1919, a small number of human ignited fires were suppressed along the southern boundary of the subsequent Ravenna Fire perimeter (Fig. 5), but more than three-fourths of the interior and northern portion of that fire had no fire suppression activity prior to 1919. At the same time as this fire, there was another of similar magnitude burning on the same forest. Fire fighters at this time were under no illusion that these were the fault of past fire suppression, rather, as Cermak (2005, p. 98) points out "*Weary firefighters realized that despite all of the lessons learned over the previous*

nine fire seasons, they could not stop a wind-driven fire in southern California chaparral. …These fires established in the minds of the firefighters from District 5 and Washington the view that southern California national forests had a special fire problem that required special fire control measures.

Other large fire events that occurred early in the 20th century are also not explained by fire suppression impacts. As early as 1913 the Barona Fire burned 26,500 ha of dense shrublands on the Cleveland National Forest in San Diego County. No lightning fires were reported suppressed during the first few years of fire reporting within the perimeter of that fire so there is no rationale for attributing this fire to suppression activities. On the Los Padres National Forest (then known as the Santa Barbara National Forest) there were several large fires in the early 1920s, but the 1932 Matilija Fire, at nearly 90,000 ha, stands out as one of the largest in California's history (Appendix E). The enormity of this fire can in no way be attributed to antecedent fire suppression actions disrupting natural fire regimes. In the prior 22 years of forest service protection, only a single lightning-ignited fire was suppressed within the 89,100 ha area of the 1932 Matilija Fire and loss of Native American burning was not likely a factor due to the extreme ruggedness of the area (Appendix E).

To summarize, on these shrubland dominated landscapes large fires over 10,000 ha are not unique to the 20th century and there is no evidence they are increasing. (Fig. 4). Such fires have occurred at least once a decade since the late 19th century, and probably throughout most of the Holocene. As with other crown fire ecosystems (Johnson et al. 2001), it is apparent that large high intensity wildfires are a predictable feature of chaparral dominated landscapes.

The role of fuel age in shrubland fires

Another prediction of the fine-grain age patch mosaic model is that chaparral shrublands do not accumulate a sufficient quantity of the easily ignited dead fuels to propagate fire until it reaches at least 20 – 30 years of age (Minnich 1987, 1995, Minnich and Chou 1997, Goforth and Minnich 2007). These authors have never directly tested this proposition, rather they have relied on indirect evidence in the form of burning patterns north and south of the US/Mexican border, and assumptions about the role of fire suppression. One empirical study that could be cited in support of their model is Green's (1981) investigation of "controlled burns." He found that under normal prescriptions of little to no wind and moderately high humidity, some shrub fuel types were difficult to burn if less than 20 years of age. Green's findings were supported by Philpot (1977) who applied the Rothermel Fire Model to chaparral fuels and showed an apparent age effect when wind was not a factor. However, Philpot also found that under high winds the fine-grain model is not supported because fires readily carry in 10 year old chaparral stands.

The notion that young chaparral acts as a barrier to fire spread, particularly under windy conditions, has been disputed from empirical studies of fire behavior (Dunn 1989, Keeley 2002, Moritz 2003, Keeley and Fotheringham 2003). The primary reason early seral stages of chaparral readily carry fire is because they are dominated by an ephemeral flora that dries each summer, producing a highly combustible fine fuel load. During these years stands commonly have a substantial cover of subshrubs and slightly woody suffrutescents such as *Lotus scoparius, Helianthemum scoparium and Calystegia macrostegia*, forming dense contiguous surface fuels (Fig. 6). A study of three year old chaparral stands in San Diego County showed that the fuel loads were substantial in these

early serial stages; > 15 tons per hectare, divided mostly between fine fuels (≤ 1 cm diameter) and coarser fuels (> 1 cm) in unburned skeletons, plus a smaller quantity of live foliage, mostly resprouts (Halsey and Keeley, in preparation). We have modeled the fire behavior for these early seral stage fuel loads and found that for fuel moisture conditions typical of late summer and fall, young chaparral is capable of rapid fire spread, even under low to moderate wind conditions (Fig. 7).

This model prediction is borne out by empirical analysis of fuel ages consumed in southern California wildfires. The 2003 Cedar and Otay fires burned through a mosaic of young and old age classes (Keeley et al. 2004). In addition, in the 2007 fires that consumed 279,700 ha, more than 40,000 ha was re-burning of 4 year old fuels from the 2003 fires (Hugh Safford, USFS, unpublished data). Although sometimes young age classes may present a barrier to fire spread, this is seldom the case under weather conditions typical of late summer and fall (Keeley 2002).

One of the complications of the fine-grain age patch model is that it apparently only applies to evergreen chaparral and not to sage scrub (Minnich 1995, Goforth and Minnich 2007). This conclusion derives from a study in Baja California that suggested differences in burn patch size between sage scrub and chaparral (Minnich 1983), and was attributed to differences in fuel structure between these two vegetation types, although distributional differences relative to human ignitions is an alternative and equally plausible explanation (Wells et al. 2004). Minnich (1995) claims that the seral stage fuel structure in chaparral prevents it from burning when young, but not so in young sage scrub (apparently this author does not believe the fine-grain age patch model applies to sage scrub). We tested this claim about age-related differences in burning of chaparral

and sage scrub by examining the distribution of age classes burned in the 10 largest fires in the Santa Monica Mountains of Los Angeles and Ventura counties (Fig. 8). The analysis demonstrated clearly that young chaparral readily burns (e.g., Fig. 8a,d,e,f,h) and that there is no consistent difference between chaparral and sage scrub.

The patterns in Figure 8 are consistent with the behavior of most southern California wildfires, which burn through many vegetation types and have fire perimeters that seldom correlate with vegetation boundaries. In the 2007 fires in southern Califonria, the extensive re-burning of 2003 fire scars comprised sage scrub and chaparral, more or less equally (Janet Franklin, unpublished data). This should not be at all surprising since there is a remarkable similarity in species composition and cover by the major growth forms between early seral stages of the two vegetation types (Keeley et al. 2005, 2006).

A corollary of the fine-grain age patch model is that large high intensity wildfires are only possible when fire suppression creates a putatively unnatural coarse-grained pattern of older dead fuels. However, empirical studies show the probability of burning does not increase in older stands of vegetation (Schoenberg et al. 2003, Moritz et al. 2004). Also, proponents of the fine-grain model have always assumed that fire suppression policy equates with fire exclusion, but this has not been the case in southern California (Moritz 1997, 2003, Conard and Weise 1998, Keeley et al. 1999, Weise et al. 2002). Indeed, contemporary fire regimes have had a much higher fire frequency than historical fire regimes (Appendix F).

Causes of megafires

The observation that a majority of megafires on our landscape have occurred in recent decades (Table 1) is commonly cited as evidence that fire suppression has

disrupted natural fuel patterns. Although the above discussion of fuels fails to support this conclusion, it does leave open the question of why the apparent rash of megafires. An obvious explanation lies in the effect of climate, since modeling studies show that weather and climate are commonly more critical in driving fire behavior than fuels in many ecosystems (Cary et al. 2006).

We hypothesize that anomalously long and severe drought is a critical factor in the generation of 20th century megafires and this is supported by a consistent pattern of prior drought and large fires (Table 1). The causal relationship between drought and megafires may vary with the timing of the fire. For example, the 2007 Zaca Fire, which burned in mid-summer, was likely facilitated by the extraordinarily low live fuel moisture for that time of year (Fig. 9). However, this explanation would not apply to autumn fires such as the 2007 Witch Fire (Table 1), since even during the extreme drought year of 2007, the live fuel moisture in October did not differ from the long term average (Fig. 9). This is because in most years the mediterranean climate results in an annual late spring and summer drought, so that live fuels are normally at their lowest physiological threshold in the autumn; the main exceptions being years with unusually wet springs (Dennison et al. 2008).

We hypothesize that the primary reason anomalously long and extreme droughts lead to megafires is through the increased generation of dead fuels in the year or years prior to the fire, and this would contribute to larger fires in summer as well as autumn. Under extended droughts the live fuel moisture drops below physiological thresholds, resulting in mortality of twigs and branchlets, or entire shrubs, and greatly increases the dead fine fuel load (e.g., Buck 1951). This was widely observed prior to the 2003 and 2007 fires

(personal observations, Lloret et al. 2004, Kelly 2007, also, http://www.wrh.noaa.gov/vef/ 2007%20CA%20AOP%20final%20web%20version.pdf).

One of the important differences between live and dead fuels is in their role in spreading fires from embers or firebrands that ignite spot fires. Although live fuels can become embers, the probability of firebrands igniting in live fuels (nearly always with fuel moisture levels above 40%) is low. Under autumn Santa Ana wind conditions, dead fuels have less than 5% moisture content and when embers land in them they have a very high probability of igniting (Fig. 10a). Although the fire front spreads rapidly under Santa Ana winds, it is always substantially slower than the wind speed (Beer 1991), and thus firebrands lofted above the fire have the potential for greatly increasing the rate of fire spread. As the quantity of dead fuels increase, the probability of long distance transport increases (Fig. 10b), and even more so in rugged terrain with high ridges and canyons. This hypothesis is supported by field observations; e.g., the fire management officer on the 2003 Cedar Fire has stated that the much greater success of long distance embers igniting spot fires was in his opinion a primary reason this fire ranks as one of the largest in state history (Richard Hawkins, USFS Cleveland National Forest, personal communication April 2004).

Whether or not these extraordinary droughts and the fires accompanying them are due to anthropogenically induced climate change, as may be the case in high elevation western forests (Westerling et al. 2006), is not known. Using the annual average Palmer Drought Severity Index for southern California we find there is a significantly negative decline between 1895 and 2007 ($P = 0.004$, $r^2 = 0.07$, $n = 113$) and when averaged per decade it is apparent that the last several decades have been drier than earlier periods in

the 20th century (Fig. 11). The coincidence of this drought and a rash of huge fires in recent years (Table 1) is likely tied to these unusual droughts, but it is too early to tell if this drought is part of a climate change induced trajectory of continued drought or part of a natural cycle. The sequence of decades with negative PDSI observed in the last 40 years is not novel if a longer time scale is considered; e.g., a similar period of drought occurred in the 19th century (e.g., 1840-1880 in Cook et al. 2004), and in other periods before that (Stahle et al. 2007). Of course even if this recent drought is cyclical, climate change may diminish the magnitude of the upturn in this drought cycle.

In addition to climate-driven temporal variation in megafires, there is also a marked pattern of spatial variation as well. These huge fires do not have an equal likelihood throughout the region because topography and vegetation distribution play important roles in determining the ultimate size of fires. It is more than mere coincidence that megafires fires (Table 1) have occurred either in San Diego County (in the southern part of the region) or in Santa Barbara/Ventura counties (in the northern part of the region). The general topography of both sub-regions supports large contiguous east-west swaths of shrubland fuels where both offshore and onshore wind flows can drive fire over very long distances. Indeed, the sites of the Matilija and Zaca fires (Table 1) are described as having "*the greatest unbroken expanses of chaparral in California*" (Cermak 2005, p. 121). Counties such as Los Angeles, San Bernardino and Riverside largely lack such topographic patterns. For example, the Santa Monica Mountains have been repeatedly burned by large Santa Ana wind driven fires, but the largest on record was a mere 17,400 ha (NPS records, SAMO). Megafires (e.g., Table 1) would not be predicted for this landscape because Santa Ana wind driven fires follow a north-south trajectory (Weide

1968) and ultimate fire size is constrained by urban development on the northern boundary of the mountains and by the Pacific Ocean on the southern boundary. Similar arguments have been offered for the apparent lack of recent megafires in northern Baja California (Keeley and Fotheringham 2001a, b), although occasionally large fires do occur south of the border (e.g., Box 1 and Vancouver's Diary from 1793 cited above).

Testing the fine-grain age patch model on southern California landscapes

It has been argued that contemporary burning patterns in Baja California represent the historical fine-grain patterns in southern California (Minnich 1983, 1995). If this is so, the distribution of fire sizes in pre-suppression California should have resembled that of Baja California (Table 2). If we take this distribution as the fixed probability distribution for fires, then knowing the number of fire starts per year allows the calculation of the average area burned per unit time, and from this the rotation interval (total area divided by area burned per year). We use lightning ignition data from two coastal mountain ranges, the Santa Ana Mountains in Orange, Riverside and San Diego counties and the Santa Monica Mountains in Los Angeles and Ventura counties (Keeley 1982, 2006), 4 per century for the former, and 2.2 per century for the latter. We estimate that with this Baja model, the fire rotation intervals would be over 650 years for the Santa Ana Mountains and over 1500 years for the Santa Monica Mountains. Clearly, to produce fire rotations sufficient to maintain these fire-adapted ecosystems (1-2 fires per century) the average area burned per year must be much greater than can be accounted for by this distribution. Either there would need to be many more ignitions than the data suggest, or, as we believe, the historical fire regime consisted of small fires punctuated at periodic intervals by large fire events.

Cellular model predictions from the fine-grain age patch mosaic model

We have presented above historical evidence for large fires. We turn now to the question of what support for the fine-grained age patch mosaic hypothesis can be found in theory. We begin with the simplest model that contains the essential parts of the hypothesis – age, ignition events, and fire size. This can be adequately represented by the 'cellular automata" class of models. In an age when there is strong and often ill-placed bias towards complex multi-parameter models (May 2004, Pilkey and Pilkey-Jarvis 2007) it is necessary to justify this choice. Fire is a complex phenomenon, and modeling its behavior upward from first principles has proven difficult (e.g., Finney 2004, Zhou et al. 2005). Therefore it makes sense to take the simplest system and see if it reproduces in a qualitative way the postulated behavior of the fine-grained hypothesis. If it does not, then there are two possibilities, the hypothesis is wrong, or there are one or more other factors that need to be considered.

But even a cellular model is more complex than is required to show that the fine-grain hypothesis cannot stand without the inclusion of a fire-stopping rule that is independent of age. It is true that the fine-grained hypothesis can work in a completely deterministic landscape. If we start with a fine-grain age mosaic (not saying how it emerged) with no ages greater than the youngest age at which a cell will burn, and have at least one ignition event per year per age patch, the age mosaic will persist forever and can be as fine-grained as the distribution of lightning ignitions. As each age-patch achieves the minimum age at which it will burn, it will be ignited, and since it will be surrounded by younger patches the fires will extinguish along the age boundaries. But if the age mosaic did not already exist, it would be impossible for it to emerge without an

age-independent stopping rule. If the landscape had a uniform age no fire would spread when the landscape was less than the minimum age (hereafter, *minage*), and the entire landscape would burn if it were greater than or equal to *minage*. The proponents of the fine-grained hypothesis must explain how the fine-grained mosaic necessary to it arises.

If we approach reality more closely by including stochasticity, the flaw in the fine-grain assumption can be made clear by a simple diagram plotting the ages on the two sides of an age boundary (Fig 12). Both sides will of course age at the same rate, so that the change in the system over time is represented by lines moving parallel to the line of no difference; further from this line if the current difference in age is larger, and closer if the age difference is smaller. If it is zero, the system moves along the line of no difference (Fig. 12). The deterministic situation just described exists when a cell burns as soon as it reaches *minage* (Fig 12a). After burning, the age of that cell drops to one of the axes (age of the cell just burned = 0). After this, the two cells age but the older cell will reach *minage* first, will burn, and return to zero on the other axis, and so on forever (Fig. 12a). But there are two ways this beautiful system can be disrupted stochastically. If ignition is not certain on a cell achieving a burnable state, then a cell can age past *minage* and the system can move into the upper right quadrant when both cells are older than *minage*. A fire at that time will set both cells to zero, the age boundary will disappear, and the system will be trapped forever along the line of no difference – that is, the cells will coalesce (Fig. 12b). Alternatively, if *minage* is not fixed, so that in some years much younger cells can burn, it is possible for the condition in one year to be, e.g., "one could burn, one cannot" and in the next to be "both will burn" (Fig 12c). As discussed above, this is what follows when an ignition event occurs during Santa Ana winds following an

antecedant drought that increases the proportion of dead fuel. And note, that since these two departures from determinism are not mutually exclusive, both can operate to break down a pre-existing age mosaic.

Adding both spatial pattern and stochasticity to the mix by use of a cellular model underscores the conclusions from these simple demonstrations. Since the proponents give no general guidance as to which factors other than age will cause a fire to go out, we incorporated this into our model by varying the probability that fire would spread from one cell to the next ("probability of propagation"), with these probabilities applying across the entire landscape. With a probability of 1, all adjacent cells greater than or equal to *minage* will burn, with a probability of 0, only the ignited cell would burn and fire size would be limited to one cell regardless of the age of the surrounding cells.

Our first series of runs varies the probability of propagation, the minimum age (*minage*) and the number of ignition events on a landscape of uniform age to explore the conditions under which a complex age mosaic will develop. To avoid the early transient conditions, the metric for our response variable is the largest fire in the last 20 simulated years. We choose a 30 x 30 landscape consisting of 900 grid cells.

Our results show that the postulated age mosaic will not develop except at low values of probability of spread. At probability values of 0.4 and above, the largest fires in the last 20 years of the simulation burn the entire landscape (Fig. 13). Varying *minage* has almost no effect, except at transitional probabilities of spread (Fig. 13). At a probability value of 0.3, greater values of *minage* result in smaller maximum fire size, though this may be a transient phenomenon.

The only possibility for the growth of a fine-grain mosaic is with a very low probability of spread. If ignitions are few (1 per year, or in the simulation 0.0004/cell/yr) and probability of propagation only 0.2, the system starts with a relatively large fire when the landscape first reaches *minage*, and then evolves towards a mixture of very small and medium size fires which appears to be the persistent state (Fig. 14a). The reason for this behavior can be gauged by noting that the average age of the landscape increases sharply and then tends to level off well above *minage* (Fig. 14). This is because the number of ignitions is not sufficient to burn all of the landscape that is burnable at this probability of propagation. These characteristics are poorly compatible with the fine-grain age patch paradigm and do not match any known fire behavior.

Increasing the ignitions by two orders of magnitude, but still with 0.2 probability of propagation also produces a complex age landscape and a pattern of burning that does resemble the ideal state postulated by the fine-grain mosaic. As with the single ignition case, there is a large fire when the landscape first reaches *minage*, but then the system evolves towards small fires each year, corresponding closely to the situation postulated by the fuel age paradigm proponents (Fig. 14b), except thathe average age of the vegetation oscillates towards a value that is significantly below *minage* (Fig 15). Because of the high number of ignitions (500 -- or 1 for each 5 cells per year), any given age patch has a high probability of being ignited even if it is not burned in its entirety, making the evolution towards a complex age mosaic possible. While this outcome demonstrates the mathematical possibility of a fine-grain mosaic, it creates an unusually young landscape, and requires a severe stopping rule in the form of a low probability of propagation, and an unrealistically dense and uniform temporal and spatial coverage by ignition sources.

With more realistic probabilities of propagation, the system rapidly moves to an all-or-nothing burn pattern, and with number of ignitions relatively unimportant (Fig. 13). We conclude that it is not possible to produce a landscape with a plausible fine-grain age distribution without unrealistic assumptions.

We also explored the problem from the other side, that is, beginning with a complex age mosaic and measuring the time it takes for this to revert to a large fire system, one in which 90% or more of the landscape burns in a single year. To show the strong effect of variable *minage* on the coalescence process (cf., Fig 12, above), we ran two sets of simulations both of which started with 900 cell landscapes in which there were patches with random ages between zero and *minage*. In the first, *minage* was held constant across simulated time at 25 years. In the second, *minage* values varied from year to year. The *minage* in a particular year was selected from a normally distributed random population with a mean of 25 and a standard deviation of 5. In both, there was only a single ignition per year. The results show both that a constant *minage* takes more time to coalesce, and that the probability of propagation has a greater effect (Fig. 16). The results for both situations demonstrate that a random mosaic will coalesce with time, and that this coalescence process is greatly accelerated if *minage* varies stochastically, as the simple model of Fig 12 would predict.

We believe that these simple models have shown that any convincing hypothesis for the evolution of the age patch structure of a chaparral landscape must have a much more complicated stopping rule than that fires will invariably go out along age boundaries. For a spatial pattern to have a stable age structure, a new age boundary must be created for

each one that is destroyed. If the fine-grain mosaic hypothesis is to be saved, how this process works must be clarified and real-world examples presented.

In summary, the only plausible conditions where the fine-grain age patch model would evolve towards a complex age mosaic would be if the environment were saturated with ignitions and if fires are patchy, which appears to be the case on certain forest types such as southwestern ponderosa pine and southeastern longleaf pine. These are ecosystems with historical patterns of frequent low severity understory surface-fire regimes made possible by an annually renewing herbaceous layer clearly separated from the tree canopy layer. Transferring that model to California shrublands cannot be justified.

CONCLUSIONS

In southern California, modern fire regimes have much in common with historical regimes. This landscape has been subject to large high intensity wildfires long before Euro-Americans settled the region and such fire events can not be blamed on fire or other land management practices. As is the case today, historical fire regimes were characterized by many small fires but the bulk of the landscape burned in infrequent massive wildfires driven by severe weather that involved high temperatures, low humidity and high winds. Often but not always these were associated with autumn Santa Ana wind events. The primary difference today is that over much of the landscape there are many more fires and the rate of burning far exceeds historical levels. This is well illustrated by the USFS fire frequency departure analysis recently completed for southern California forests (e.g., Appendix F). Thus, the idea that fire suppression has altered fuel

structure in ways that make this landscape more vulnerable to large fires is demonstrably false for southern California.

Historically, climatic variation probably caused considerable fluctuation in the timing and size of fires. Human ignitions have been part of the picture for thousands of years, but the most important change in the region has been the 20th century increase in human populations, and the proliferation of human-ignited fires, coupled with demographic patterns that have resulted in increased human mobility and dispersion into chaparral landscapes. Although fire suppression policy has been in effect for over a century, aggressive fire control has been in effect for about half that time. Its increasing technological capacity and impressive organizational advances have not been able to counteract the effect of this ever increasing ignition source.

The present analysis points towards several management recommendations. Attempts to recreate a mythical fine-grain mosaic are doomed to fail. Burning large areas on a 15 to 20 year rotation in small patches would require massive investments and a significant risk of damaging escapes. The substantial environmental cost of the expanded network of fuel and firebreaks that would be required would also need to be considered (Ingalsbee 2006). History suggests that the accumulated work of decades would be swept away in a large fire under severe weather. Fuel treatments aimed at modifying fuels and maintaining an age mosaic dominated by young fuels will be a barrier to fire spread only under benign conditions, and should not be used with the expectation that they will stop rapidly spreading wildfires. Reduced fuels do have value in moderating fire intensity and providing defensible space that will facilitate fire operations. Left to themselves, they will do little to limit the extent of a fire. Fuel modification will be of greatest value at the

wildland-urban interface, but must be done judiciously and with due regard to for the potential negative impacts on biodiversity conservation. Application of fuel treatments beyond this interface zone may have tactical value, but much research is still needed on the most cost-effective placement of these treatments.

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TABLE 1. Megafires of ~50,000 ha or larger in southern California (fire size from FRAP database, except 1889 Santiago Canyon Fire based on the analysis in the present paper and 2007 Witch Fire from CalFire website), and associated duration of drought prior to fire, measured by the Palmer Drought Severity Index (PDSI scale is -6 to 6, with negative values being drier than average). All fires were human ignited (either direct incendiary fires or indirectly due to powerlines). Fires where Santa Ana winds were a factor some time during the fire are indicated, however, all fires were associated with weather that included high than normal temperatures, very low humidity and erratic winds

								Antecedent drought	
Year	Fire losses	County[&]	Month ignited	Santa Ana winds (days)	Area (ha)	Struct-ure losses	Deaths	Months w/ Negative PDSI	Ave PDSI for months
1889	Santiago Cyn	Orange	Sept	yes (3)	125,000 (200,000?)	0	0	[&&]	-0.25
1932	Matilija	Santa Barbara	Sept	yes (>5)	89,100	0	0	23	-2.22
1970	Laguna	San Diego	Sept	yes (2.5)	70,500	382	8	14	-1.81
1985	Wheeler #2	Ventura	July	no[$]	49,700	26	0	7	-1.23
2003	Cedar	San Diego	Oct	yes (2)	109,500	2,400	15	54 out of prior 61	-2.36
2006	Day	Ventura	Sept	yes (1)	65,500	11	0	12	-2.11
2007	Zaca	Santa Barbara	July	no[$]	97,300	1	0	20	-2.99
2007	Witch	San Diego	Oct	yes (3)	80,200	1,736	2	17	-3.62*

[&] county where the bulk of the fire burned

[$] Although outside the Santa Ana wind season, severe fire weather including extreme temperatures, low humidity and erratic winds were factors

[&&] monthly records unavailable; based on paleo reconstructions for summer drought, PDSI for 1887 = -.65, 1888 = 0.39, 1889 = -0.47

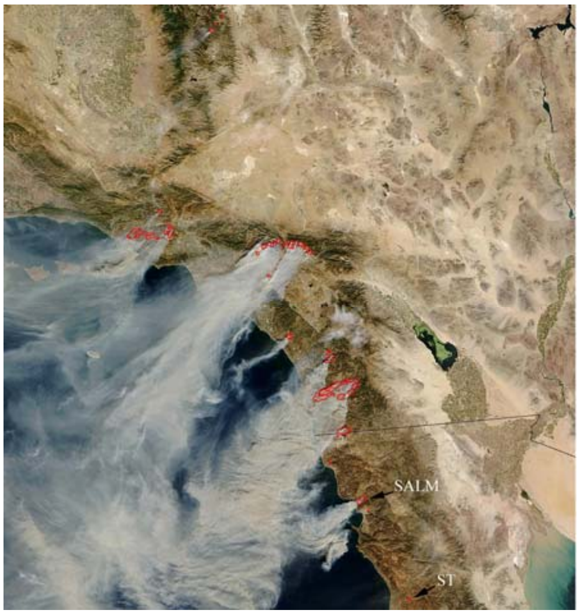
* for the 6 months prior, all months were below -5.00 PDSI

TABLE 2. Frequency of fire events by size class observed in Baja California and considered to be representative of the natural fire pattern in southern California (Strauss et al. 1989, based on Minnich 1983) and calculated fire rotation intervals based on documented lightning fire densities. For the Santa Ana Mountains we used an average of 4 lightning ignited fires per million ha per year reported for Orange County (Keeley 1981) and for the Santa Monica Mountains an estimate of 2.2 lightning fires per million ha per year (Keeley 2006).

Median Size Class (ha)	No.	%	Calculated area burned (ha) in 100 years, based on number of lightning fires/million ha/100yrs	
			Santa Ana Mtns	Santa Monica Mtns
40 – 100	167	43.2	12,096	5,140
100 – 200	84	21.8	13,080	5,559
200 – 400	61	15.8	18,960	8,058
400 – 800	29	7.5	18,000	7,650
800 – 1600	19	4.9	23,520	9,996
1600 – 3200	17	4.4	42,240	17,952
3200 – 6400	4	1.0	1,920	816
6400 – 12,800	4	1.0	3,840	1,632
12,800 – 25,600	1	.3	19,891	8,453
25,600 – 51,200	0	0.0	0	0
> 51,200	0	0.0	0	0
Total area burned (ha) in 1 million ha of landscape after 100 years			153,547	65,257
Rotation Interval (yrs)			651	1,532

Box 1. Santa Ana winds and fires in southern California

These foehn winds are a synoptic weather condition developing from a high pressure cell in the Great Basin coupled with a low pressure trough off the Pacific Coast. They are an annual occurrence in spring and autumn, but the latter season follows an ~ 6 month drought and results in the most extreme fire weather of any region in the country (Schoeder et al. 1964). They are often more severe in the Santa Ana Mountains than in other parts of southern California (Appendix B-1), with wind speeds over 160 kph (44 m s^{-1}) recorded there during some events (Froke 1993, p. 19).



Santa Ana wind driven fires and smoke in 2003 from Ventura County, USA to San Antonio de Las Minas near Ensenada, Mexico (arrow). Note the apparent lack of Santa Ana winds on the fire further south near Santo Tomas (arrow at bottom of panel) due to effects of the Gulf of California and San Pedro Martir (see Keeley and Fotheringham 2001a,b). Image captured by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra satellite on October 26, 2003 http://earthobservatory.nasa.gov/ **NaturalHazards /shownh.php3?img_id=11799)**

Understanding the burning patterns reported for the 1889 Santiago Canyon Fire requires recognition of several characteristics of Santa Ana winds. Although they are typically described as northeast winds, the orientation of the winds varies both spatially and temporally. For example, in the Santa Ana Mountains the primary orientation of winds changes from a northeast wind in the northern part of the range to an east wind further south (Appendix B-2). In addition, on the leeward side of mountains the differential heating and cooling of valleys vs slopes, and land vs ocean, produce thermal forces that can disrupt the foehn flow (Edinger et al. 1964, p. 12, Rosenthal 1972, p. 5.19-5.23). As a result, during mid-day there is often a reverse flow (Appendix B-3) that can spread fire in erratic and unpredictable directions. These alternating winds have profound impact on large fire behavior. As described by Orange County Fire Battalion Chief Mike Rohde (email: 1 Feb 2008), “It’s not uncommon for onshore winds to either develop at low elevations or at least to ‘stall’ a Santa Ana during peak daytime convective heating. The Santa Anas will often regain strength at night as the foehn wind doesn’t have to ‘fight for dominance’ with the solar driven diurnal wind. Santa Anas often peak shortly before or just after dawn because of this condition. With this kind of behavior the fire receives the best of all possible burning conditions by either (1) developing high intensity fire runs in canyons with accompanying strong thermal smoke columns (caused by slope and fuel driven fire), and then the deposition of fire brands and long range spotting as the Santa Anas aloft shear off the smoke column, causing heavy spotting downwind [see also Albini 1983], or (2) by stretching out the fire’s perimeter when up-canyon runs are followed by the resurfacing of Santa Ana winds.”

Commonly Santa Ana wind driven fires are pushed by this intense off-shore flow for only one to several days, however, these fires typically continue burning under the milder on-shore flow for a week or more. It has been observed that this on-shore flow following Santa Ana wind events is significantly stronger than the normal onshore breezes (Mike Rohde, personal communication, Nov 2007). The reasons for stronger onshore flow are not known but may be tied to the substantial drop in ocean surface temperature offshore during Santa Ana wind events (Hu and Liu 2003, Trasviña et al. 2003). Alternatively, the perception of this more intense onshore flow could be due to the fact that it is pushing the very dry Santa Ana air masses back on shore (Dave Sapsis, Cal Fire, personal communication 10 April 2008).

FIGURE LEGENDS

FIG. 1. Close up of the northern fire perimeter of the 1878 Tujunga Cañon Fire and location of fire scar dendrochronology study area sampled by Kerr (1996) that is outside the fire perimeter. The fact that Kerr (1996) did not detect the 1878 fire would be expected and should not have been used by Goforth and Minnich (2007) as evidence that the fire perimeter map was in error.

FIG. 2. The daily fire activity for the 1889 Santiago Canyon Fire based on newspaper accounts (see text and Appendix A for details). Fire runs are indicated with arrows and associated dates are based on newspaper accounts cited in the text. These reports show that during the first day (Tuesday, 24 Sept) the fire burned at least as far south as El Toro in the coastal foothills and in the mountains a distance of ~ 40 km. On Wednesday the fire continued burning southward both in the mountains and along the coastal plain, at one point threatening the city of San Juan Capistrano. By the third day reports show the fire had burned about 50 km north-south in the mountains and to the present day town of De Luz. Strong east winds then drove the fire towards the Santa Margarita ranch house. When the offshore flow abated, the onshore flow carried the fire eastward towards Temecula. At this point the fire was likely driven by the steep topography, daytime down-canyon flowing winds that push fires eastward, as is the case with modern fires in this region (Schroeder 1959). The newspapers report burning east of Encinitas but it is unclear if this was part of the Santiago Canyon Fire.

FIG. 3. Fire plume from 19th century fire in the San Gabriel Mountains, Los Angeles County. From Kinney (1900, p. 45), with legend "Forest Fire in Sierra Madre Mountains, July 22, 1900. Taken Twenty-five miles from fire" (see Appendix A: Los Angeles Daily Times, 23 – 28 July 1900). Photographs of other high intensity southern California shrubland fires ion pages 43 and 49.

FIG. 4. Fire size during the latter part of 19th and throughout the 20th century (based on the FRAP database, plus USFS data on 2007 large fires, and additional 19th century fires not in the FRAP database but with clear estimates of size in newspaper reports in Appendix A. Regression analysis for year vs fire size, $r^2 = 0.000$, $P = 0.67$, n = 671 for all fires 1,000 ha or larger and $r^2 = 0.001$, $P = 0.73$, n = 87 for fires 10,000 ha or larger.

FIG. 5. 1919 Ravenna Fire (name according to the CalFire FRAP database; named the Tujunga Fire in Show 1945, and the N. Fork Pacoima Canyon Fire by the Los Angeles County Fire Department). Since record keeping began in 1910 the only record of lightning fires suppressed within the fire perimeter is one 2 ha fire with point of origin indicated by a star. Point of origin for anthropogenic fires are indicated with closed circles, most of which were less than .1 ha and the largest was 150 ha (individual fire records from USFS Angeles National Forest). Only prior fire substantive enough to be included in the FRAP database was the 1878 Tujunga Cañon Fire, shaded area on lower right.

FIG. 6. Seral stage chaparral in spring 2007, 5 years after the Bouquet Canyon Fire, dominated by resprouting *Adenostoma fasciculatum* and ephemeral subshrubs established from seed (primarily *Lotus scoparius*) in northern Los Angeles County (photo by Jon Keeley). During the 2007 Buckweed Fire, 2700 ha of this Bouquet Canyon Fire were re-burned.

FIG. 7. BehavePlus model results using a custom fuel model for early seral stage chaparral fuels similar to those depicted in Figure 6, although from a site in San Diego County; dead fuels were 6, 4, and 3.58 Mg/ha (tonne/ha) for 1, 10 and 100 hr fuels, respectively, and live fuels were .38 and 2 Mg/ha and 30% and 50% moisture for herbaceous and woody fuels, respectively; (Halsey and Keeley in preparation). Rothermel equations that are used in the Behave Model have short comings when applied to mature chaparral where live fuels dominate, however, in these young seral stands dead fuels dominated and the bulk of the dead fuels were within 75 cm of the soil surface.

FIG. 8. Age classes of chaparral and sage scrub burned by the 10 largest fires in the Santa Monica Mountains (data from Dr. Robert Taylor, Santa Monica Mountains National Recreation Area, Jan 2008).

FIG. 9. Live fuel moisture in the widespread chaparral shrub *Adenostoma fasciculatum* from Santa Clarita in northern Los Angeles County for 2006, 2007 and the 27 year

average (http://www.fire.lacounty.gov/Forestry/FireWeatherDangerLiveFuel Moisture.asp).

FIG. 10. BehavePlus 4 model results on (a) probability of firebrands igniting and (b) spotting distance from wind driven surface fire; using high load dry climate shrub S5 fuel model and wind speed of 80 km/hr.

FIG. 11. Decadal average for the Palmer Drought Severity Index for the southern California region (the first decade comprised only the years 1895-1899 and the last decade (2000-2007). Error bars illustrate that all decades have had some wet years but on average the region has experienced drought over the past half century. Analysis of variance of decadal mean PDSI was significant $P < 0.001$.

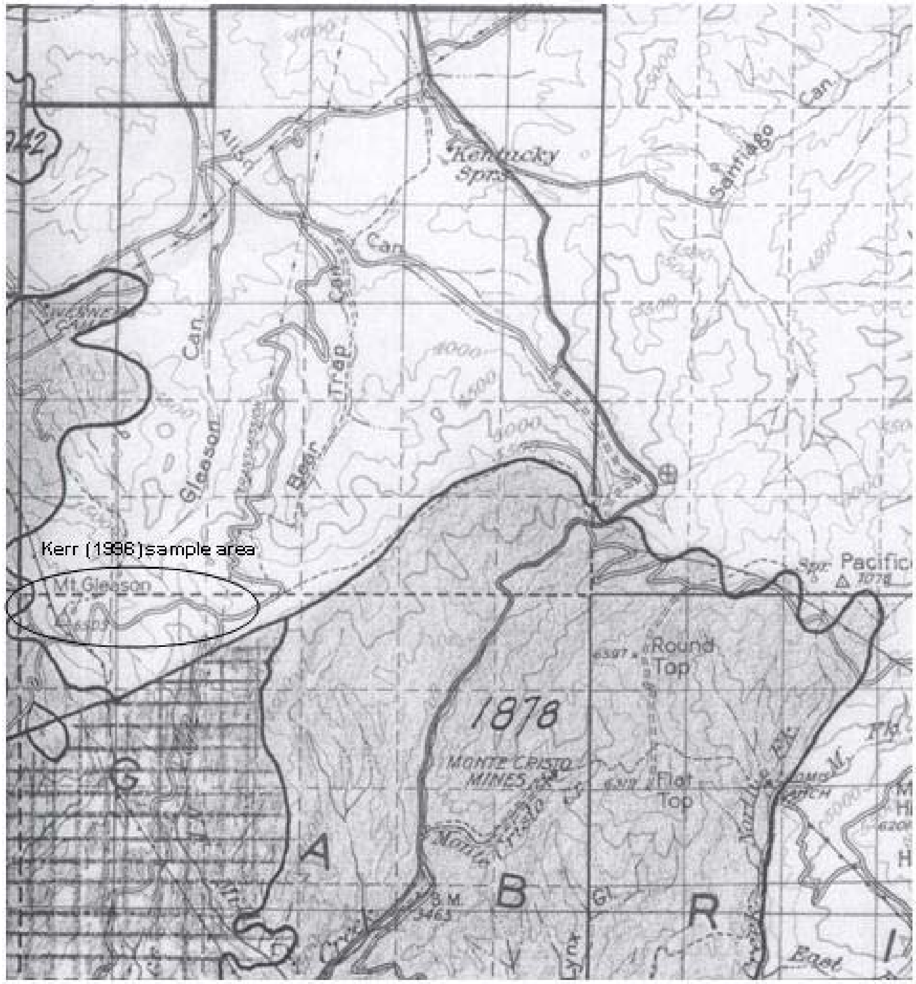
FIG. 12. Perpetuation or loss of an age boundary. A. The deterministic behavior alleged in the "fuel paradigm". An age boundary persists because the older vegetation will first reach "minage", receive an ignition, and burn. If fire is certain, the boundary will persist forever. B. If random variation in timing of ignition allows vegetation on both sides of the boundary to reach an age at which they will burn the age boundary will disappear at the next fire. Over the whole landscape, this process will tend towards coalescence of the age mosaic. C. If minage varies, so that at some times more of the landscape is liable to burn, the age boundary is much more likely to be eliminated. From this, one would predict that variable "minage" would cause coalescence to occur more rapidly, with or without random ignition. Figure modified from Zedler and Seiger (2000).

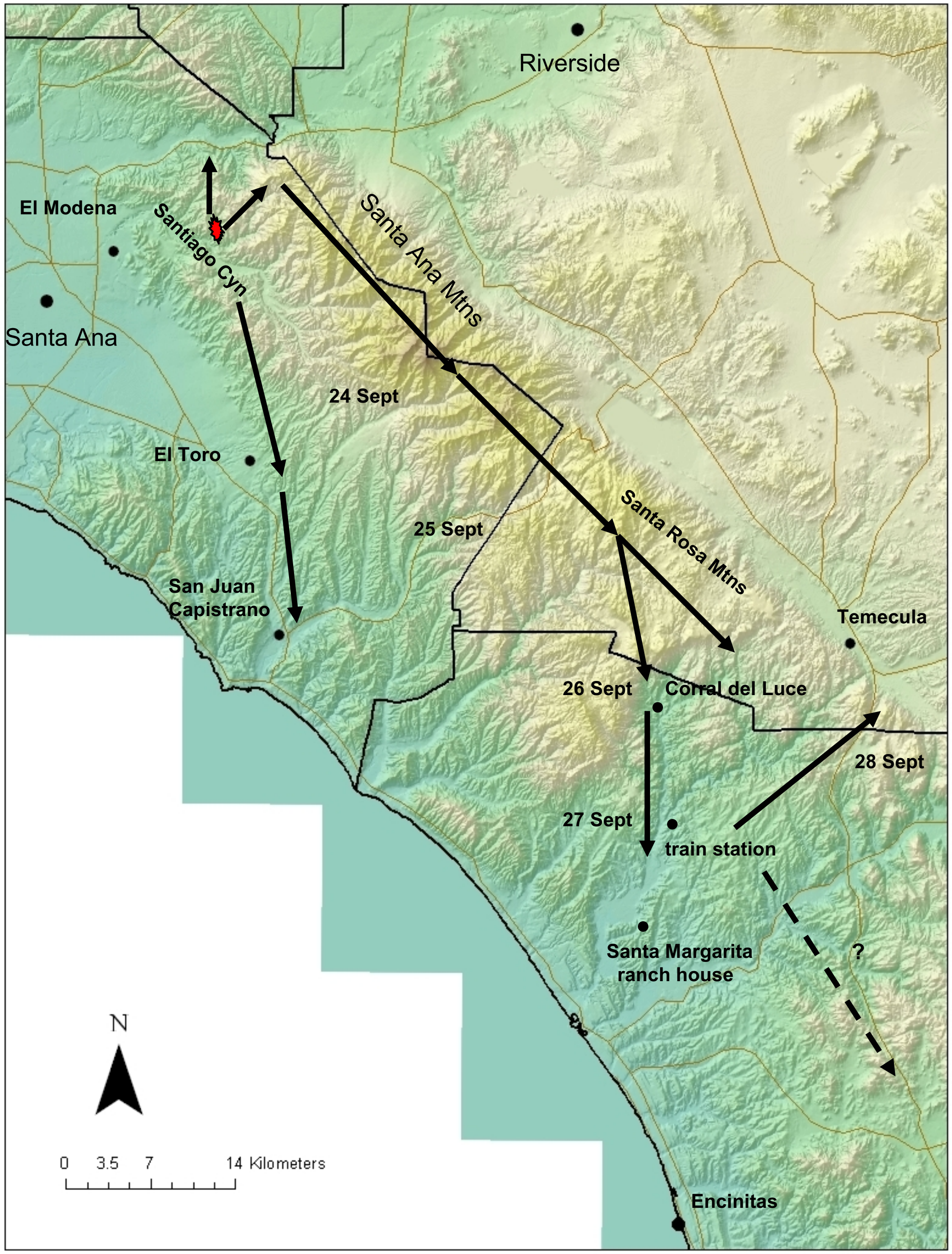
FIG. 13. Effect of minage (youngest age at which vegetation will burn) and probability of propagation (probability that fire will transfer to an adjacent unburned cell) on the maximum area burned during the last 20% of the simulation period (to minimize the effect of transient conditions). The simulation is run for 500 years for a 900 cell landscape. Beyond a probability of propagation of 0.5 the system is locked into very large fires, regardless of minage, or, as will be shown below, the number of ignitions.

FIG. 14. Simulated results for a 2500 cell universe with a minage of 20, a probability of propagation from one cell to the next of 0.2, and 1 or 500 ignitions per year. At one ignition per year, this low probability of propagation produces a quasi-stable situation with a variable but generally a small area burned per year. At 500 ignitions per year, the system oscillates with a period that corresponds to minage, towards a stable situation of consistently small area burned per year.

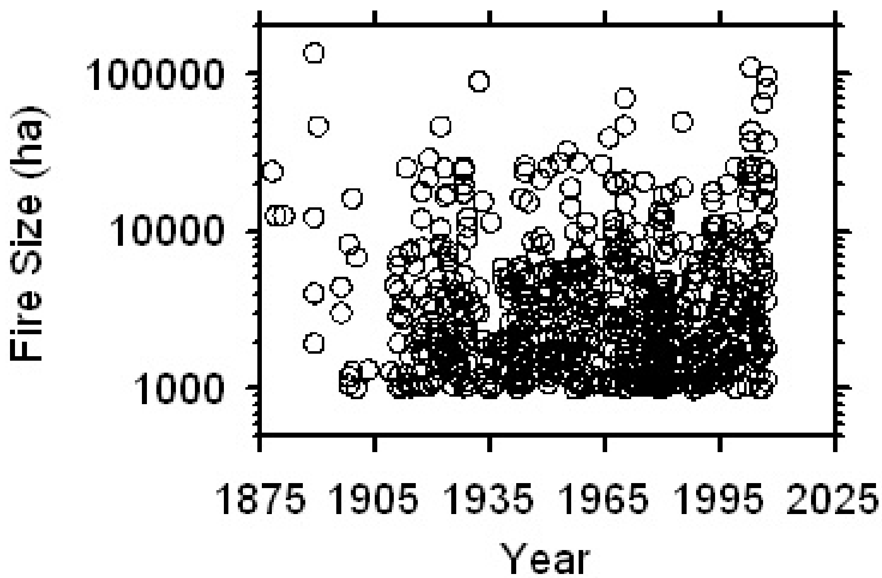
FIG. 15. Data from the simulations run for Fig. 14 expressed as average age of the landscape. With only one ignition per year, the average age increases consistently and then tends to level off. This is because the low probability of spread insures that only a small part of the landscape will burn despite the fact that many cells are well beyond the minage. In contrast, with saturating ignitions (lower line), the average age of the landscape stablilizes at about half of minage because any area that achieves minage will burn.

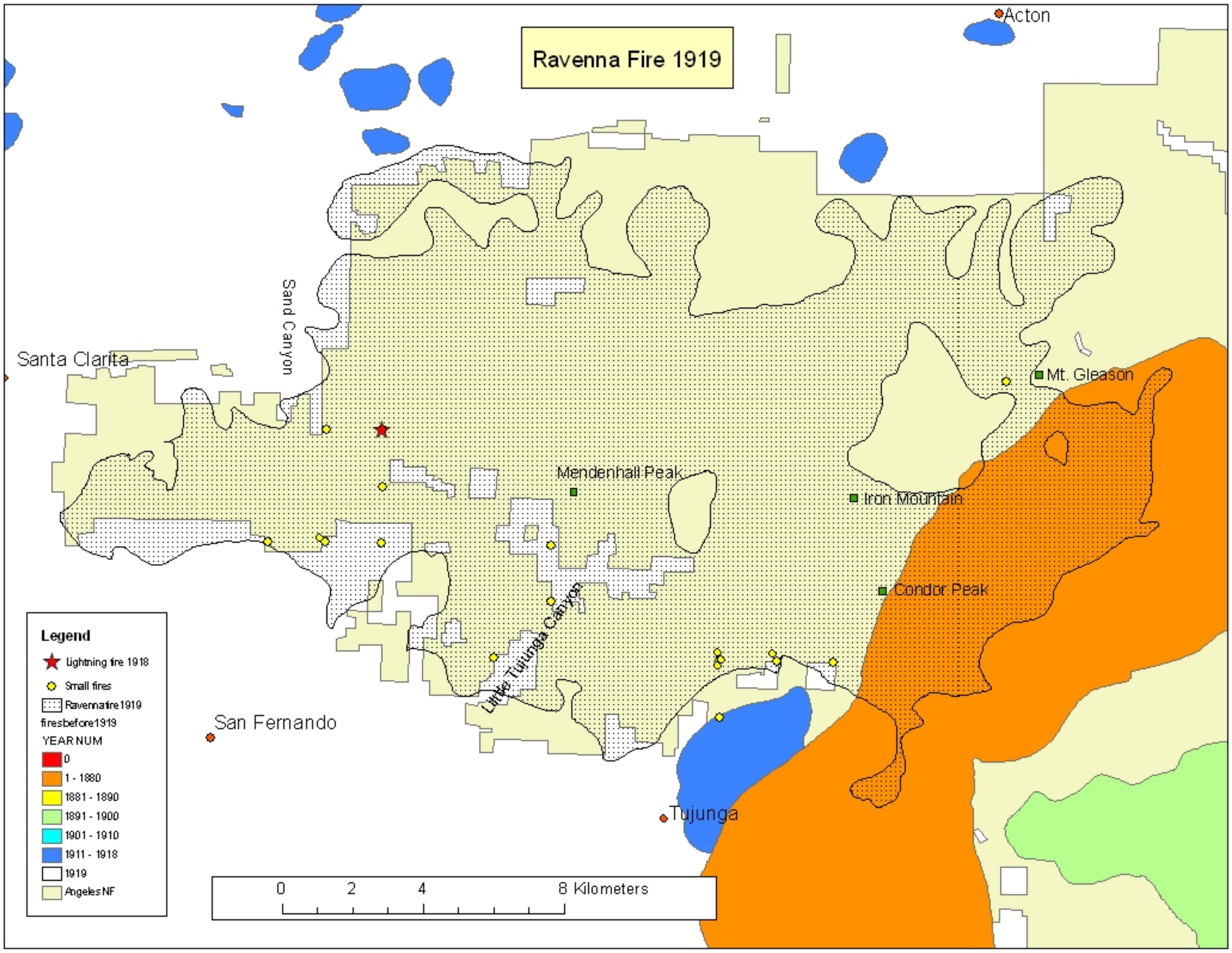
FIG. 16. Comparison of “time to coalescence” starting from a random distribution of ages in simulated landscapes subjected to constant (solid circles) and variable (open circles) minimum ages at which the cells will burn for different probabilities of spread from one “burning” cell to the next. Error bars are plus and minus one standard deviation of the mean for samples of 25 runs. Note that the error bars for the variable case are contained within the symbols. For this run, the “landscape” consists of 900 grid cells, and minimum age is taken as 25 years. Above a probability of propagation of 0.4, all possibilities evolve toward eventual coalescence, but this occurs in less than 1/4th the time when the minimum age is allowed to vary normally about the mean with standard deviation of 5 years.


Kerr (1998) sample area
Mt Gleason
Kentucky Sprs
Santiago Can.
Gleason Can.
Bear Trap Can.
Pacific
Round Top
Flat Top
1878
MONTE CRISTO MINES
Monte Cristo
G
A
B
R
East

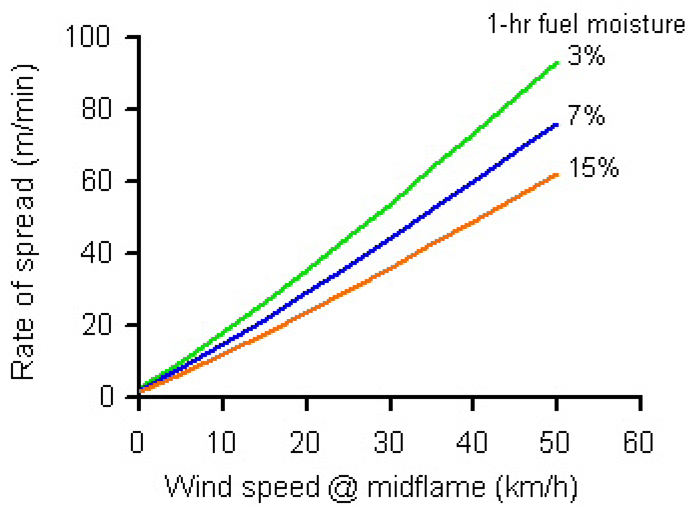


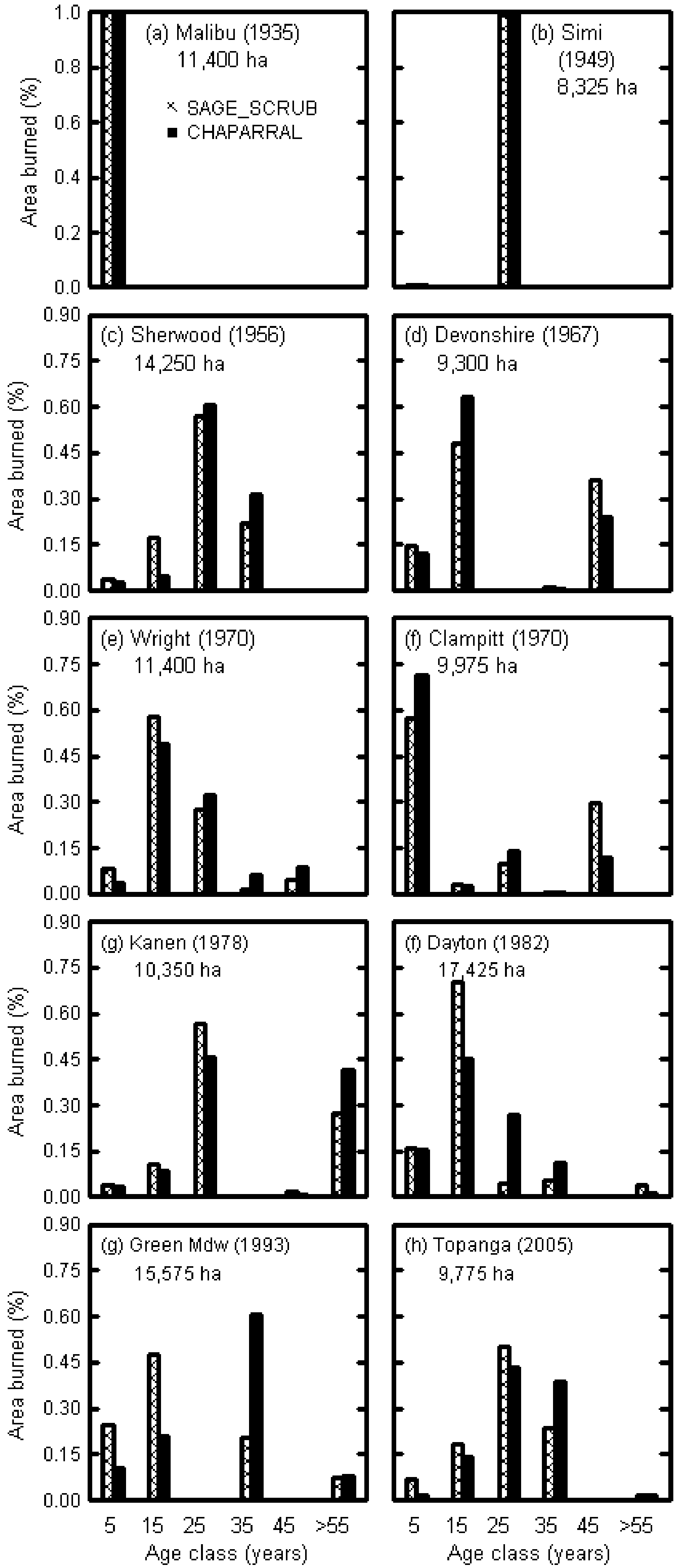
Riverside
El Modena
Santiago Cyn
Santa Ana
Santa Ana Mtns
24 Sept
El Toro
25 Sept
Santa Rosa Mtns
San Juan Capistrano
Temecula
26 Sept
Corral del Luce
28 Sept
27 Sept
train station
?
Santa Margarita ranch house
N
0 3.5 7 14 Kilometers
Encinitas


100000
10000
1000
Fire Size (ha)
1875 1905 1935 1965 1995 2025
Year

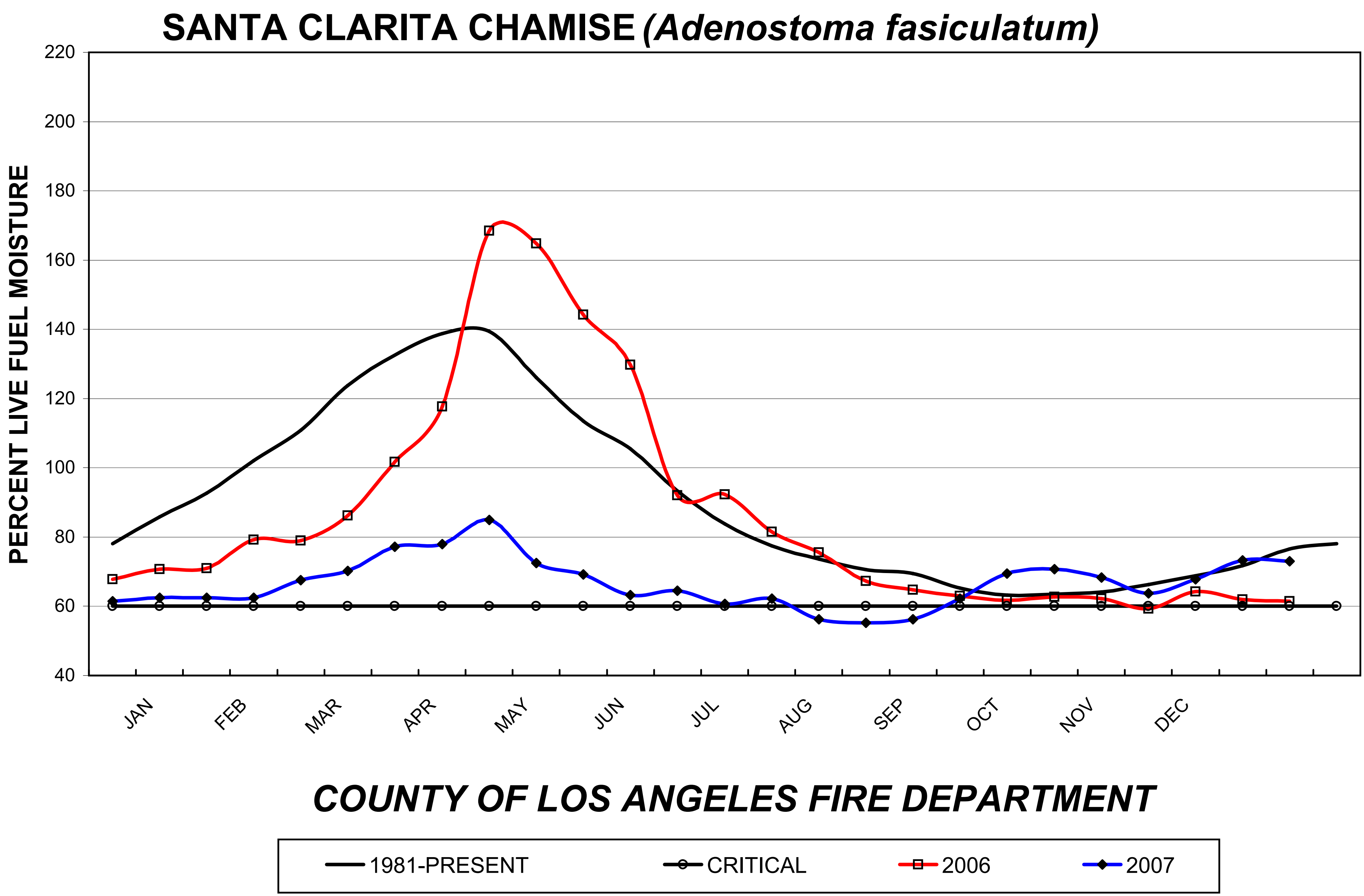


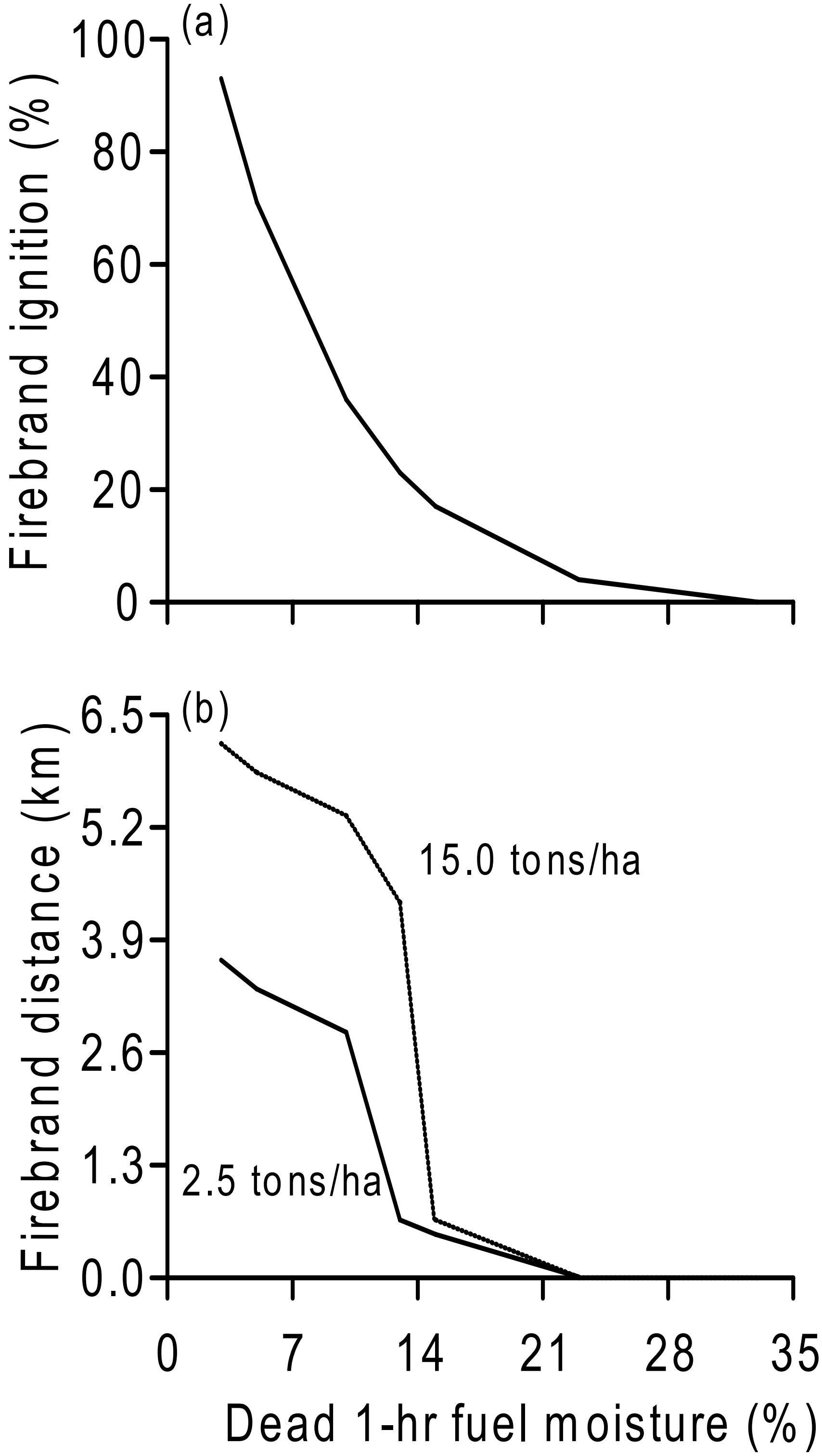
Ravenna Fire 1919
Acton
Santa Clarita
Sand Canyon
Mt. Gleason
Mendenhall Peak
Iron Mountain
Condor Peak
Little Tujunga Canyon
San Fernando
Tujunga
Legend
Lightning fire 1918
Small fires
Ravennafire1919
firesbefore1919
YEAR NUM
0
1 - 1880
1881 - 1890
1891 - 1900
1901 - 1910
1911 - 1918
1919
Angeles NF
0
2
4
8 Kilometers

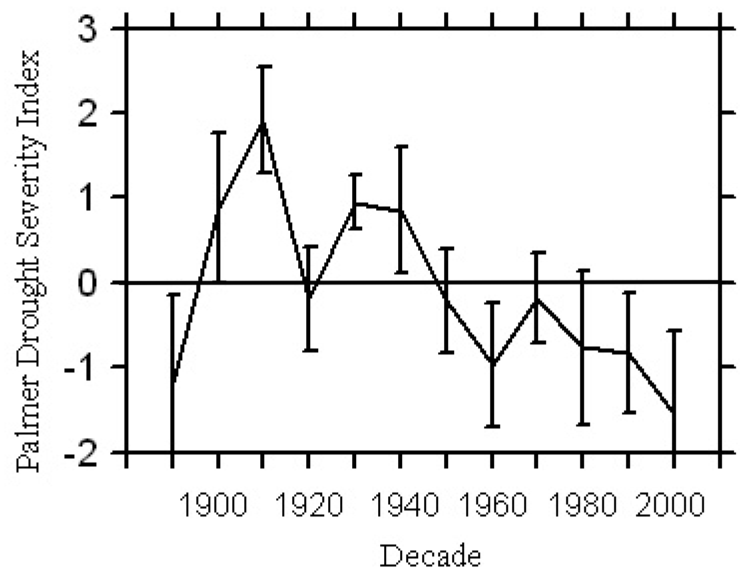

1-hr fuel moisture
3%
7%
15%
Rate of spread (m/min)
100
80
60
40
20
0
0
10
20
30
40
50
60
Wind speed @ midflame (km/h)

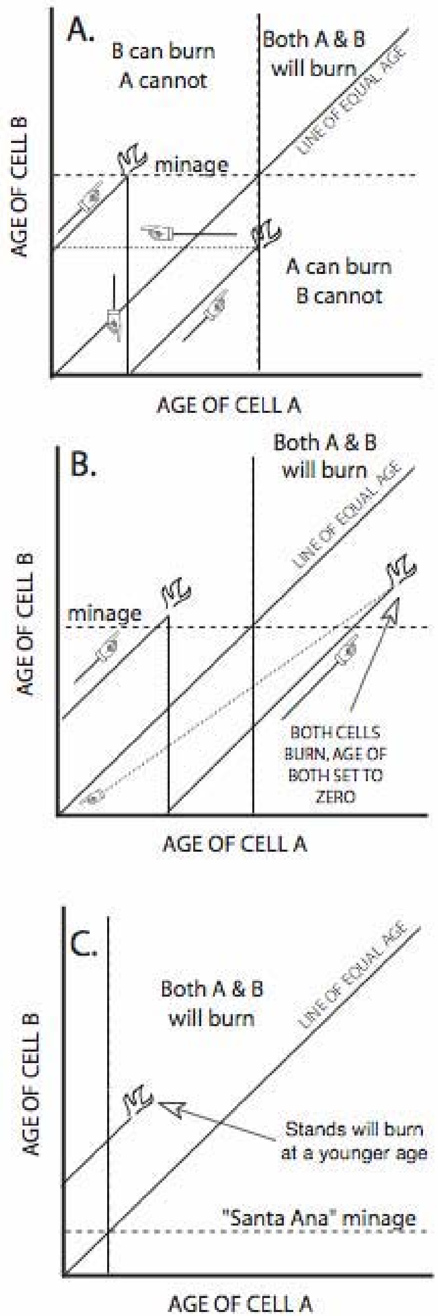


(a) Malibu (1935)
11,400 ha
SAGE_SCRUB
CHAPARRAL
(b) Simi
(1949)
8,325 ha
(c) Sherwood (1956)
14,250 ha
(d) Devonshire (1967)
9,300 ha
(e) Wright (1970)
11,400 ha
(f) Clampitt (1970)
9,975 ha
(g) Kanen (1978)
10,350 ha
(f) Dayton (1982)
17,425 ha
(g) Green Mdw (1993)
15,575 ha
(h) Topanga (2005)
9,775 ha
Area burned (%)
Age class (years)
5
15
25
35
45
>55

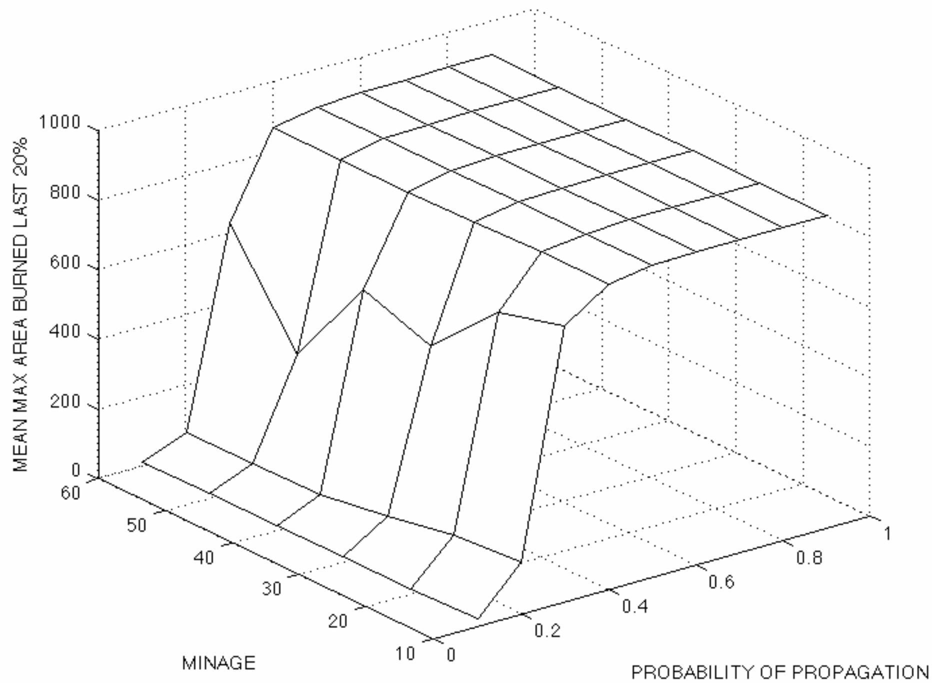

SANTA CLARITA CHAMISE (Adenostoma fasiculatum)
PERCENT LIVE FUEL MOISTURE
220
200
180
160
140
120
100
80
60
40
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
COUNTY OF LOS ANGELES FIRE DEPARTMENT
1981-PRESENT
CRITICAL
2006
2007


(a)
Firebrand ignition (%)
100
80
60
40
20
0
(b)
Firebrand distance (km)
6.5
5.2
3.9
2.6
1.3
0.0
15.0 tons/ha
2.5 tons/ha
0
7
14
21
28
35
Dead 1-hr fuel moisture (%)

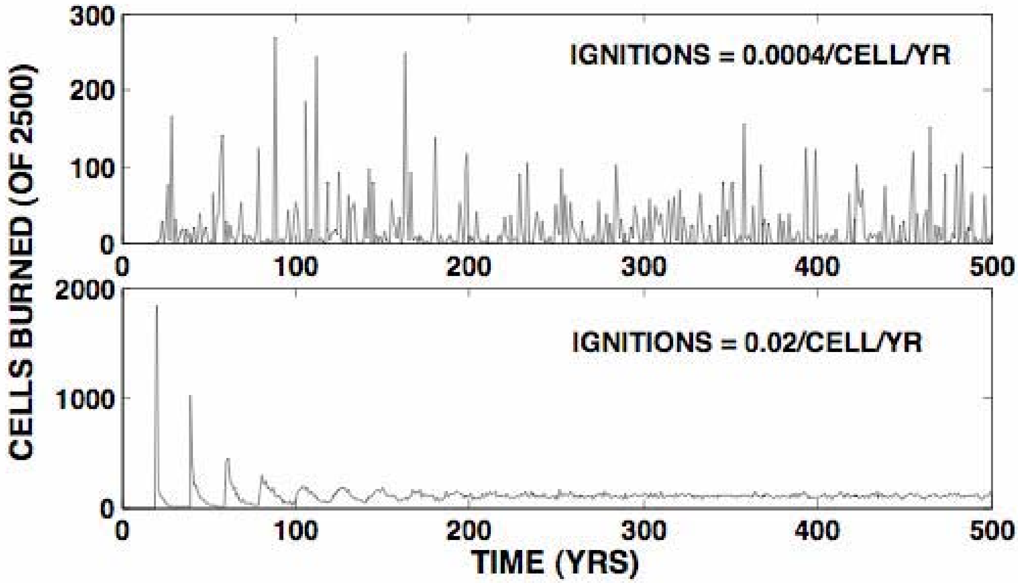

Palmer Drought Severity Index
3
2
1
0
-1
-2
1900 1920 1940 1960 1980 2000
Decade



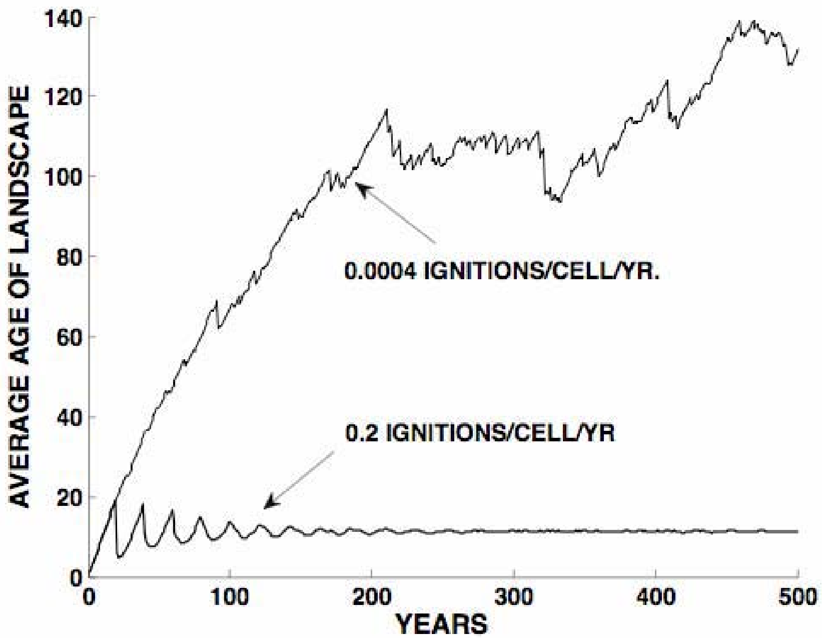
A.
B can burn
A cannot
Both A & B
will burn
LINE OF EQUAL AGE
minage
A can burn
B cannot
AGE OF CELL B
AGE OF CELL A
B.
Both A & B
will burn
LINE OF EQUAL AGE
minage
BOTH CELLS
BURN, AGE OF
BOTH SET TO
ZERO
AGE OF CELL B
AGE OF CELL A
C.
Both A & B
will burn
LINE OF EQUAL AGE
Stands will burn
at a younger age
"Santa Ana" minage
AGE OF CELL B
AGE OF CELL A



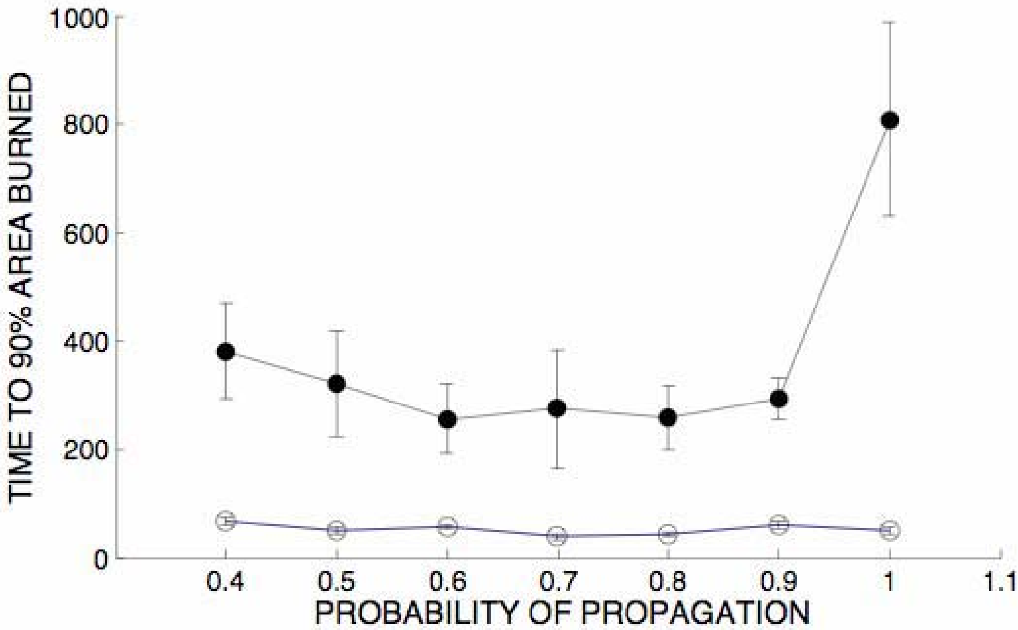
MEAN MAX AREA BURNED LAST 20%
1000
800
600
400
200
0
60
50
40
30
20
10
MINAGE
0
0.2
0.4
0.6
0.8
1
PROBABILITY OF PROPAGATION



IGNITIONS = 0.0004/CELL/YR
IGNITIONS = 0.02/CELL/YR
CELLS BURNED (OF 2500)
TIME (YRS)
0
100
200
300
400
500
1000
2000



140
120
100
80
60
40
20
0
AVERAGE AGE OF LANDSCAPE
0.0004 IGNITIONS/CELL/YR.
0.2 IGNITIONS/CELL/YR
0
100
200
300
400
500
YEARS



TIME TO 90% AREA BURNED
PROBABILITY OF PROPAGATION
1000
800
600
400
200
0
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1